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Perceptual-motor Learning and Transfer: Effects of the Conditions of Practice on the Exploratory Activity in a Climbing Task

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Foreword

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General Introduction

Introduction

Most of our everyday goal-directed actions are performed proficiently in complex and dynamic environments. The performance contexts usually differ from day to day, but our goals are generally still achieved indicating that we are skillfully coupled to our environment. For example, when going from home to work, streets may be more or less busy, weather conditions may change the surfaces and/or the visibility, stress may arise due to late departure from home, however (most of) everyone arrive at the office on time. Such adaptable behavior is acquired, improved throughout life, which shaped to the development of perceptual-motor skills. But how does previous experience contribute to such skilled perceptual-motor behavior? How do individuals learn to continuously adapt their actions to the environmental context? What practice conditions facilitate skill acquisition and transfer?

Developing perceptual-motor skills to be able to perform in various contexts is necessary in different sporting activities. For example, in lead climbing, performers are confronted to unknown routes designed specifically for each event. Before attempting their climbs, performers are given only six minutes to visually inspect the route from the ground (the minimal height of the route being 12m). Then, they have six minutes to attempt to reach the top of the route, without falling (a fall marking the end of the attempt). The ranking is defined by the last hold controlled or used by the competitors with either hand, those reaching the top being firsts (IFSC, 2019). Thus, being able to "read" the opportunities for actions that the route offers to perceive how to chain the actions safely and successfully is a key aspect of performance for competitive climbers.

What links performers' perception and action is their exploratory activity (E. J. Gibson, 1988; J. J. Gibson, 1966). Through the interactions with their environment, performers can discover / reveal opportunities for actions, called affordances (J. J. Gibson, 2015). In the climbing example, visual and haptic modes of exploration are necessary for performers to reveal perceptual information enabling to control movements adaptively to the climbing environment. Although the importance of the exploratory activity for perception and action was emphasized in the motor development literature (Adolph, Bertenthal, Boker, Goldfield, & Gibson, 1997; E. J. Gibson, 1988; Thelen, 1995), the dynamics of the exploratory activity when learning complex perceptual-motor skills remains to be investigated. Studies showed that exploratory activities (notably the gaze activity) are different between experts and novices, but the studies generally relied on perceptual-cognitive tasks (Mann, Williams, Ward, & Janelle, 2007) and considerably simplified the complexity of the actions to perform and the complexity of the environment (van Andel, McGuckian, Chalkley, Cole, & Pepping, 2019). Therefore, the first aim of this thesis is to examine how exploratory activity changes within individuals with learning in a complex perceptual-motor task.

If skilled behavior is supported by effective exploration of the environment, a solution to foster skill transfer to new environments (such as the new route designed for climbing competitions) may reside in the development of generalizable exploratory activity during practice. Improving generalization of learning was historically proposed through the variability of practice hypothesis (Schmidt, 1975). The benefits of variable practice would occur when the tasks performed during the acquisition phase are parameter variations of the same movement class. In this case, the benefits of variable practice would be revealed by better performance in retention and transfer tests in comparison to a constant practice. Another question was then raised regarding how to best schedule task variations within a practice session. A proposed hypothesis claimed that, although repetitive schedules (such as blocked practice) enable to reach better performances during acquisition, schedules with higher contextual interference during practice (such as in random practice) would lead to better learning, especially in retention and transfer tests (Magill & Hall, 1990; Shea & Morgan, 1979). Thus, these extensively studied hypotheses from information-processing approach to learning advocate that variations during practice would improve the generalization of internal schemata or would facilitate the elaboration of an action plan (Magill & Hall, 1990; Schmidt, 1975). However, the studies testing these hypotheses usually rely on discrete movement tasks performed in laboratory (Schöllhorn, Mayer-Kress, Newell, & Michelbrink, 2009; Wulf & Shea, 2002). In complex perceptual-motor tasks involving multiples degrees of freedom, transfer may be plausibly explained by the ability to reveal and pick up information for movement selection and control in different contexts during the unfolding performance. Thus, a second aim of this thesis is to investigate the effects of variable practice conditions on skill learning and transfer, with a particular interest on how such conditions affect the learners' exploratory activity in comparison to constant practice conditions.

Studies in perceptual and motor learning showed that although participants follow the same learning protocol, the practice effects can differ importantly amongst learners (R.

Withagen & van Wermeskerken, 2009; Zanone & Kelso, 1997). Thus, the implementation of practice conditions that are externally imposed to the learners to obtain the expected learning outcomes seems questionable. Indeed, learning dynamics are quite variable between learners and recent studies showed that an optimal ratio between exploration and exploitation must be found by learners to benefit at best from practice (e.g., Komar, Potdevin, Chollet, & Seifert, 2019). Thus, regularly imposing a new performance context during variable practice may become detrimental if the externally imposed rate of exploration does not enable learners to exploit the learnt movement solutions in their behavioral repertoire. For example, imposing the rate at which the task difficulty is increased during practice may suit some learners but lead some others to continuous failure (Y.-T. Liu, Luo, Mayer-Kress, & Newell, 2012). Thus, a third aim of this thesis is to examine whether giving learners some control over their practice schedule can help to offer practice conditions that are more respectful to their individual dynamics.

To address these three aims, this thesis adopts the of the *Ecological Dynamics* theoretical framework to capture skill learning and transfer in the light of the dynamical interactions between the performers and their environment.

Pillars of the Ecological Dynamics Theoretical Framework

With a main interest in goal-directed behavior in sporting contexts, the Ecological Dynamics framework aims at grasping the complexity of sport athletes performing and learning within their performance environment. To do so, the *Ecological Dynamics* framework builds on tools and concepts from *Ecological Psychology* and *Dynamical system theory*.

The *Ecological Dynamics* framework emphasizes that (i) the appropriate scale of analysis to understand skill learning is the performer-environment system, as skilled behavior is considered to arise from the improved functional fit between an individual and a particular performance context, (ii) performers' actions emerge from interacting constraints through self-organization and nonlinear dynamics (Araújo & Davids, 2011; Button, Seifert, Chow, Araújo, & Davids, 2021).

The Ecological Scale: Informational-based Interactions between Performers and their Environment

Building on James Gibson's (1979) proposal, Ecological Dynamics emphasizes that human behavior cannot be understood independently from its environmental context

(Araújo, Hristovski, Seifert, Carvalho, & Davids, 2017). This perspective postulates that cognition, perception, and action emerge from the interactions between the performer and the environment at *the ecological scale*. It means that, the influence of the environment on performers and vice-versa is reciprocal and mutual, making *the performer-environment system* the proper unit of analysis to study goal-directed behaviors (J. J. Gibson, 2015; Richardson, Shockley, Fajen, Riley, & Turvey, 2008).

The coupling between the performer and the environment is supported by the active pickup of information. The performer's activity is embedded within *ambient energy arrays* (e.g., optic, acoustic, mechanical) from which patterns specifying the state of the relationship between the environment and the performer can be extracted (J. J. Gibson, 2015; Stoffregen, Mantel, & Bardy, 2017). These patterns constitute *information* that can be picked-up to guide movements accurately. James Gibson (1966) stressed that the pick-up of information is an active process, which is performed by what he called the *perceptual systems*. For example, the ambient optic array is made of light reflected by objects, but optic information obtained by the visual system depend on the observer's eye-height and motion. The actions of the perceptual systems often cooperate to better differentiate information (J. J. Gibson, 1966). For example, climbers often look and touch the handholds to reveal how they can be grasped and used. The activity of the perceptual systems was classified as *exploratory*, due to their important contribution to perception, and to be differed from the *performatory* activity of the executive systems (latter called action systems) responsible of behavior more globally (e.g., locomotion, grasping) (E. J. Gibson, 1988; J. J. Gibson, 1966; Reed, 1996). Thus, information is tightly coupled to movement as one constrains the other dynamically.

Learning to extract information enables to perceive opportunities for action offered by the environment, opportunities that James Gibson called *affordances* (J. J. Gibson, 2015). The theory of affordances posits that the environment is not perceived in terms of its physical properties but in terms of how the performer can act in it (J. J. Gibson, 2015). Therefore, affordances are specific to each performers' action capabilities which also involves that affordances are dynamic, as performers' action capabilities are susceptible to change over time (Fajen, Riley, & Turvey, 2008).

Eleanor and James Gibson (1955) proposed that perceptual learning leads to an increased ability to discriminate information from the ambient energy arrays. Three processes support perceptual learning (Jacobs & Michaels, 2002, 2007). First, according to performer's intentions, perception and action would aim to solve different problems (Jacobs & Michaels, 2002). The convergence between the performer's intentions and task goal is referred to as the *education of intention* (Davids, Araújo, Hristovski, Passos, & Chow, 2012). Second, the *education of attention* (also known as *attunement*) consists in learning to pick-up more reliable information to guide action (Fajen & Devaney, 2006). Finally, controlling action accurately requires the process of *calibration*. Calibration consists of mapping information to movement (Fajen, 2007). It requires performers to be sensitive to their own action capabilities to correctly detect information in intrinsic units (Fajen, 2005, 2007). The processes of attunement and calibration are further presented in **Chapter 1**. Thus, skill learning consists in improving the functional fit between an individual and a particular performance context through information-movement couplings.

To account for the continuous interactions between performers and their environments through informational coupling, the Ecological Dynamics framework relies on a dynamical system perspective to explain persistence and change in the human behavior (Davids, Handford, & Williams, 1994; Kugler, Scott Kelso, & Turvey, 1980).

The Nonlinear Dynamics of Behavior: Complexity of the Performer-Environment System

An important ontological consideration of the Ecological Dynamics framework is to consider performers as *complex adaptive systems*. Although the definition of a *complex system* remains under debate, three characteristics can describe a complex system and distinguish it from a complicated one: (i) complex systems are composed of many parts, (ii) these parts are interconnected by relationships or interactions and (iii) the combined effects of the parts (*synergies*) produce outcomes that can be unexpected (Northrop, 2010). These characteristics can be retrieved at different levels within the system. For example, a human being is a complex neurobiological system composed of different subsystems (e.g., the central nervous systems) which are themselves composed of smaller interacting parts (e.g., cells). Thus, complex systems demonstrate a *hierarchical organization*, where each level has its own laws, but the laws of a new level cannot defy the laws at a lower level. One of the challenge is to understand how the human movement system manages to coordinate the large number of degrees of freedom that compose the human body to achieve goal-directed behaviors (Bernstein, 1967).

In this perspective, human behavior is characterized by *self-organization* and *emergence*. *Self-organization* means that the system behavior is not prescribed by a centralized controller, but it is shaped by the interactions between the system components (Richardson & Chemero, 2014). The system's behavior is *emergent* because its organization cannot be predicted on the basis of the subcomponents properties, but behavior is organized by both the internal and external constraints applied to the system. Indeed, performers are also considered as *open systems* as they are sensitive to their environmental conditions and continuously exchange energy with the environment (Davids, Glazier, Araújo, & Bartlett, 2003). Thus, the regulation of behavior is distributed over the performer-environment system (J. J. Gibson, 2015; Warren, 2006)

This non-proportional relation between complex system's inputs and outcomes reflects the *nonlinear dynamics* of human behavior as changes in initial conditions of the system can produce disproportionate changes in the whole system behavior later in time. For example, changing the orientation of an handhold on a climbing route was shown to affect the whole body posture of the climber (Seifert, Boulanger, Orth, & Davids, 2015). Such nonlinear changes in behavior can be observed at different timescales, from infants' development, skill learning or single performance achievement. This *sensitivity to initial conditions* reflects that the system organization is susceptible to change unpredictably, demonstrating a *chaotic behavior*. However, chaotic behavior distinguishes from random behavior by determinism. Indeed, change in system organization cannot be predicted, but they are determined by the constraints affecting the system behavior. The constraints both limit the range of possible behaviors of the system and enable these behaviors, offering a *phase space* containing all the hypothetical organizations that the system may adopt (Button et al., 2021, p. 28).

Newell (1986) proposed that goal-directed behavior is shaped by three sources of *constraints*. First, *organismic constraints* are composed of the structural and functional characteristics of the human movement system (e.g., climbers can use handholds according to the dimensions of their hands and their grip strength). They are also conceived as the internal constraints of the human movement system. Then, constraints that are external to the human movement system are divided into environmental constraints and task constraints. On one hand*, environmental constraints* refer to the constraints that are not manipulated by the coach, instructor, or experimenter. These pertain to the physical conditions (e.g., the weather, gravity, the air composition) and the sociocultural context of performance. On the other hand, external constraints that can be manipulated are called *task constraints*. These constraints can affect the task goal and/or how the task goal can be achieved (Newell, 1986). Goal-directed movements emerge from the dynamic interactions between these three sources of constraints, and a small change in any source of constraints may lead to important changes in the emerging performed movement (Newell, 1996).

Individual learners demonstrate, even prior to practice, a repertoire of spontaneous behavioral tendencies (Schöner, Zanone, & Kelso, 1992). The landscape of these behavioral tendencies forms the *intrinsic dynamics* of the learners, composed of *behavioral attractors*. In this view, learning is defined as the reorganization of the intrinsic dynamics of the learners so that the to-be-learned pattern becomes an attractor (Schöner et al., 1992). According to the initial intrinsic dynamics of the learners, studies using a bimanual coordination paradigm showed that when acquiring a new coordination pattern, the whole intrinsic dynamics is affected, but this reorganization takes different forms according to the individual's initial dynamics and its relation to the coordination pattern to-be-learned (Kostrubiec, Zanone, Fuchs, & Kelso, 2012; Zanone & Kelso, 1992, 1997). They showed that when the to-be-learned pattern *cooperates* with the intrinsic dynamics, learning is characterized by a shift, with an already stable coordination pattern that is close to the to-be-learned losing stability in favor of the trained coordination pattern (Zanone & Kelso, 1992). But when the learner's dynamics *competes* with the task demand (i.e., no existing stable attractors are sufficiently close to the to-be-learned coordination), a qualitative change of the intrinsic dynamics occurs as a new behavioral attractor is acquired, in addition to prior behavioral tendencies (Zanone & Kelso, 1992). Thus, learning consists of interactions between the learner's intrinsic dynamics and constraints of the performance context, dynamically destabilizing and reorganizing the intrinsic dynamics.

In summary, the Ecological Dynamics framework apprehends human behavior at the ecological scale, considering that perception, action, and cognition are distributed over the performer-environment system. The performer and his/her environment are considered as dynamical systems coupled by information and movement. The organization of behavior emerges from the interactions of constraints, both internal and external to the performer, that give rise to nonlinear dynamics over multiple timescales.

The Ecological Dynamics Perspective on Skill learning and Transfer

Considering the performer-environment system as dynamical and self-organizing with interconnected subsystems through informational-based interactions offers the foundations to examine and study skill learning and transfer. In this regard, skill learning is conceptualized as a search process within a *perceptual-motor workspace* representing the landscape of available movement solutions satisfying the set of constraints in which performance occurs (Newell, McDonald, & Kugler, 1991; Pacheco, Lafe, & Newell, 2019). Indeed, when learning a complex perceptual-motor skill, learners demonstrate nonlinear changes in the performed coordination patterns (Chow, Davids, Button, & Rein, 2008; Nourrit, Delignières, Caillou, Deschamps, & Lauriot, 2003). The learning dynamics are composed of periods of *exploration*, during which learners discover different movement solutions, and periods of *exploitation* where learners repeatedly perform the same movement solution (Hills et al., 2015; Komar et al., 2019; Pacheco et al., 2019). Alternation between periods of exploration and exploitation would enable learners to stabilize multiple movement solutions while navigating through the perceptual-motor workspace (Komar et al., 2019). However, it should be stressed that both periods entail variability in the movement system behavior. While exploration may reflect unstructured movement variability (or large displacements across different areas of the workspace), periods of exploitation are characterized by reduced movement variability around a movement solution (or a small displacements within a region of the workspace) (Sternad, 2018).

Based on this conceptualization of skill learning and the processes entailing perceptual learning precedingly presented, the Ecological Dynamics framework proposed a three-stage learning model: (i) search and exploration, (ii) discovery and stabilization, and (iii) exploitation (Button et al., 2021; Davids et al., 2012). The stage of *search and exploration* involves the exploration of the degrees of freedom in the perceptual-motor system to achieve a task goal. At this stage, learners try to align their intentions to the task goal to direct their attention toward relevant information for action (i.e., they educate their intentions) (Button et al., 2021). The stage of *discovery and stabilization* consists of attempting to reproduce the identified movement solutions by reorganizing the previously exaggerated constriction of degrees of freedom. Learners discover the limits of their movement solutions and search new information-movement couplings which, with practice, help learners converge their attention toward more reliable information for action (i.e., they educate their attention). Finally, at the stage of *exploitation*, learners are able to immediately adapt to the situational demands by taking advantage of the system degeneracy. Degeneracy is defined as “the ability of elements that are structurally different to perform the same function or yield to the same output” (Edelman & Gally, 2001, p. 13763). The exploitation of the degeneracy of the perceptual-motor system supports the system flexibility to perform effectively in dynamically interacting constraints (Seifert, Komar, Araújo, & Davids, 2016). Thus, learners become better at scaling their perceptual-motor system to information (i.e., calibration).

Fostering learners’ exploration during practice was deemed to improve learning rate (Chow, Davids, Button, & Renshaw, 2016; Schöllhorn et al., 2009). Given that complex perceptual motor tasks often enable multiple movement solutions to successfully achieve the task, the aim is (i) to avoid that learners plateaued during practice by exploiting a single movement solution and (ii) that they search and discover different functional movement solutions (the set of successful solutions is also called solution manifold, Müller & Sternad, 2004). Thus, fostering exploration would enable to develop skilled movement solutions both adapted and adaptable to the performance context (Seifert, Komar, et al., 2016). *Adapted* movement solutions require that the performed coordination patterns satisfy the set of constraints in which performance occurs. *Adaptable* movements require that the coordination patterns demonstrate *stability* by being reproducible and robust to perturbations while allowing *flexibility* to vary and adjust movement to the local and temporary constraints.

As change in the constraints is the rule rather than an exception, one of the challenges in skill learning is to provide practice conditions that facilitate the generalization (transfer) of perceptual-motor skills to new performance contexts, i.e., practice inducing *positive transfer* (rather than neutral or negative). Transfer is usually defined in terms of the similarity between the learnt task and the transfer task, so that *near transfer* refers to similar tasks (e.g., transfer from indoor to outdoor climbing) and *far transfer* corresponds to tasks with very different demands (e.g., transfer from football to climbing) (Rosalie & Müller, 2012). In ecological dynamics, *skill transfer* is defined as the capacity to use prior experience under a particular set of constraints to perform under a different set of constraints (Newell, 1996; Seifert, Wattebled, et al., 2016). In this view, transfer would depend on the relationship between the individual’s intrinsic dynamics and the dynamics of the new task

(Button et al., 2021, p. 137; Seifert, Wattebled, et al., 2016). In a situation of cooperation, the behavioral tendencies support performance in the new task, facilitating the emergence of successful behaviors. This situation refers to a *specific transfer*. When the relationship between the intrinsic dynamics and the task dynamics do not cooperate closely, and only general skills can support performance*, general transfer* occurs. In the case of competition between the intrinsic dynamics and task dynamics, *negative transfer* may occur if the existing behavioral tendencies are detrimental or do not provide the necessary basis for performance in the new context. Therefore, the Ecological Dynamics framework stresses that the design of the practice conditions must be *representative* of the performance context where skills developed during learning are aimed to be used (Pinder, Davids, Renshaw, & Araújo, 2011). A *representative learning design* would support skill transfer by ensuring that performer-environment interactions developed through information-movement couplings during practice can be retrieved in the performance context (Button et al., 2021).

In summary, the overall view of ecological dynamics on skill learning and transfer is well summarized by Newel (1996, p. 398):

> *"A skilled performer changes the solution to the movement coordination and control problem according to the various changing demands of the organism-environment interaction and to the pursuit of the task goal. In general, a skilled performance may also be characterized by an anticipation of the consequences of future events including one's own action. This anticipation, or prospective control, is based on the pickup and utilization of task-relevant information and is a factor that underscores the tight link between movement information and movement dynamics in action."*

Objectives and Plan of the Thesis

The main objective of this work is to examine the changes in performers' exploratory activity that accompany skill learning and support skill transfer. Exploratory activity refers here to the actions of the perceptual systems performed to pick up information as defined by Eleanor and James Gibson (1988; 1966). As expressed in the last sentence of Newell's citation (1996), the dynamics of changes in coordination patterns, which have been captured during the acquisition of different complex perceptual-motor skills (e.g., Chow et al., 2008; Komar et al., 2019; Nourrit et al., 2003), are supported by underlying changes in information-movement couplings. By highlighting these changes through the modification of the exploratory activity in function of practice and performance contexts, this work aims to contribute to the understanding of the role of exploratory activity in (i) the development of skilled behaviors at the learning timescale and (ii) the adaptions of these skilled behaviors to different set of constraints.

The second objective is to examine whether infusing variability in practice with task variations designed by manipulating the learning environment could foster skill learning and transfer. The manipulation of the constraints applied on learners' performance is a lever proposed to enhance the exploration of different functional movement solutions to achieve the task goal (Chow et al., 2016; Davids, Button, & Bennett, 2008). This exploration is expected to enlarge the learners' motor repertoire in comparison to more repetitive practice conditions (Lee, Chow, Komar, Tan, & Button, 2014). Moreover, the confrontation to different learning environments also increases the variability in the experienced information-movement couplings during practice (in comparison to a constant practice condition). Such variability was shown to help the generalization of learning through attunement (e.g., Fajen & Devaney, 2006). Thus, it may also help the generalization of the learners' exploratory activity, which would facilitate skill transfer. This work aims to investigate the effect of infusing variability on the learners' repertoire and exploratory activity.

The third objective is to examine whether giving learners the opportunity to control their practice schedule would offer learning conditions that are more respectful of the individual dynamics. As previously described, a small change in the set of constraints can lead to unpredicted changes in behavior, giving rise to nonlinear and individual-specific learning dynamics (e.g., Chow et al., 2008). Thus, externally imposing new sets of constraints may be unfavorable to the optimization of the ratio between exploration and exploitation of movement solutions, which may increase interindividual differences in learning outcomes. A solution is to propose an adaptive practice schedule, which may be set up by involving the learners in the implementation of their learning environment (this point is further developed in **Chapter 3**). In this regard, this work aims to investigate the effect of giving learners the opportunity to control their practice schedule on their repertoire and exploratory activity.

This thesis is composed of three sections. The first section presents three chapters reviewing the literature. The **Chapter 1** is a narrative review examining exploratory activity in ecological dynamics and discussing its relationship to performatory activity and skill learning. The **Chapter 2** focused more specifically on visual exploration and gaze behavior in relation to goal-directed behavior. The **Chapter 3** is a systematic review of the studies investigating motor learning interventions with variations in the task constraints during practice. Based on these reviews, the objectives and hypotheses of this work are further developed in conclusion of the present theoretical section. The second section is composed of four chapters presenting two experiments (**Chapters 4, 5, 6 and 7**). The first experiment used a climbing task to investigate the modifications of learners' visual and haptic exploratory activity with practice and to determine to what extent the acquired perceptual-motor skill and the learners' exploratory activity would transfer to environments with novel properties. This experiment is presented in **Chapter 4**. The second experiment also used a climbing task and was designed to (i) examine whether infusing variability in practice would foster skill learning and transfer and (ii) investigate whether variable practice conditions could be optimized by giving learners the opportunity to control the frequency of variations in the task and, by extension, the amount of total variability encountered during practice. The group and practice effects of this experiment are examined at three levels: the learners' behavioral flexibility (**Chapter 5**), their performance dynamics (**Chapter 6**) and their visual exploratory activity (**Chapter 7**). These seven chapters can be read independently from each other as they are written in the form of research articles. The final section is a general discussion gathering the theoretical, methodological, and applied contributions of this work.

Chapter 1: Exploring to Learn and Learning to Explore

Introduction

Exploration is the continuous and active process through which individuals reveal and pick up information during the control of action (E. J. Gibson 1988; J. J. Gibson 1979/2015). From an ecological psychology perspective, information resides as patterns in ambient energy arrays (e.g., optical, acoustic, mechanical) that specify the state of the relation between the environment and the individual. From this point of view, exploration underpins the relation between information and movement as the energy arrays are structured by the properties of the environment and the motion of the individual (J. J. Gibson 1979/2015; Mantel, Stoffregen, Campbell, and Bardy 2015; Stoffregen, Mantel, and Bardy 2017). When the information specifies relevant individual-environment relations, individuals perceive opportunities for action, that is, affordances (J. J. Gibson 1979/2015). Said otherwise, through exploratory perceptual-motor activity, individuals reveal energy arrays leading to the pickup of information about affordances that is used to adapt to the environment (E. J. Gibson, 1988).

Authors have tended to differentiate between exploratory and performatory actions (J.J. Gibson, 1966; E. J. Gibson, 1988; Reed, 1996). An underlying proposal has been that exploratory action reveals information that is subsequently utilized in the control of performatory action (e.g., Kretch and Adolph, 2016). Exploration is often considered as a period of information-gathering to satisfy an intention (Adolph, Eppler, Marin, Weise, & Wechsler Clearfield, 2000; E. J. Gibson, 1988; Kretch & Adolph, 2017). In this context, exploratory and performatory actions are often differentiated as the former is thought to precede the latter in development. Whilst such distinction has been meaningful in the developmental psychology literature when applied to other domains of psychology such as expert perceptual-motor control in sport, this has led to the development of methods that separate the reciprocity of perception-action (e.g., McGuckian, Cole, Chalkley, Jordet, and Pepping 2018). Indeed, a contemporary view of perception-action, that builds on James Gibson's (1966) original perspective is that the process of visual perception is context-dependent and relative to the body and action capabilities of the performer (Wagman & Morgan, 2010). Although this view is well-established in ecological psychology, this important proposal is often omitted in the sports skill acquisition literature, particularly during intervention studies aimed at examining the role of exploratory movements in learning.

Given that a central tenet of ecological psychology is that perception is embedded in the continuous flow of action and vice-versa, in the current manuscript, we aim to develop a view of exploratory and performatory action that reflects an embodied-embedded approach to skilled behavior (Richardson et al., 2008). We argue that studying the dynamics of changes in exploration during learning could provide valuable information on how perception-action is developed, with specific consideration of how learners become more skilled at perceiving and acting in relation to affordances with respect to sport-specific behaviors (Seifert, Komar, et al., 2016). Central to this view is an affordance-based control framework (Fajen, 2005), which proposes two learning processes in the development of perception and action: (i) attunement and (ii) calibration. First, attunement is characterized by the differentiation of information that supports the pickup of more reliable patterns in the energy arrays to guide action (Fajen & Devaney, 2006; J. J. Gibson, 1966). Second, calibration consists in finding an appropriate scaling between information and action capabilities (Fajen, 2007). Indeed, as individuals' action capabilities change over time (e.g., action capabilities can change with fatigue), recalibration facilitates continuous adaptation that supports the visual control of action (Fajen, 2005, 2007). Despite the large body of literature discussing the importance of exploration to develop perception-action, exploratory activity is rarely studied in sports skill acquisition. To address this gap in the literature, we propose the need to examine the exploratory actions used to generate and scale reliable information for affordances, to better understand "how" individuals become more skilled during learning.

In sum, this critical review will focus on how exploratory activity can give rise to perception-action during the acquisition of perceptual-motor skills in sport. We will first consider the methods used in ecological psychology to investigate exploration. Although this distinction appears insightful to understand the development of action systems (Reed, 1996), we propose that these methods cannot be applied to all performance contexts. Indeed, in many complex sporting environments such as climbing (Seifert et al., 2018), exploratory and performatory actions can appear tightly linked in tasks where performers need to continuously adjust their relationship with the environment to guide on-going and future activity. Second, we consider the dynamics of exploratory activity during learning. In studies of expert sport populations, it is often implied that the amount of exploration decreases as performers become more attuned to the relevant properties of the environment (Mann et al., 2007). We will discuss such assumption and present exploration as a process that, under appropriate practice conditions, supports attunement and calibration, thus, continuously revealing the appropriate fit between the environment and the perceiver's action capabilities. Finally, we will present some challenges and considerations to design interventions where individuals can learn to explore. Rather than learning a specific movement, we propose that skill acquisition should focus on how performers could develop exploratory behavior: (i) that is useful in various performance contexts; and (ii) that enables maintenance of active prospective control during performatory activity.

Explore to Reach a Task-Goal: Exploration and Performance

Exploratory Actions: Explore to Perform

James Gibson (1966) proposed that perception is an active process that does not rely on passive sensory units, but on the activity of perceptual systems. Gibson differentiated exploratory (or investigative) activity achieved by these perceptual systems from the performatory (or executive) activity achieved by the action systems. Following Gibson's initial work, Reed (1996) further differentiated exploratory and performatory activities to understand the development of functional systems, which are the systems that enable individuals to use resources in their environment to achieve their goal. Reed (1996) proposed that exploratory actions are those that are aimed at scanning the environment for information whereas performatory actions are those that alter the substances and surfaces of the environment. This distinction is useful as animals, especially those like humans, with a head differentiated from the rest of the body, are able to scan their environment for information while acting in their environment. For example, during bipedal locomotion, humans have the capacity to maintain a prospective control in locomotion or to initiate other activity (Reed, 1996).

The differentiation between performatory and exploratory activity is in line with perspectives in developmental psychology (E. J. Gibson, 1988). Eleanor Gibson differentiated performatory actions from exploratory actions that are information-gathering, to understand how infants discover opportunities for action. For instance, E. J. Gibson et al. (1987) measured the visual and haptic exploration of infants in a task where they had to traverse different surfaces. Exploratory activity was defined as the period before initiation of locomotion on the manipulated surface (i.e., when the infants were leaving a starting platform). This study showed that the duration of haptic and visual exploration depended on the properties of the surfaces (whether they were rigid or not) and on the mode of locomotion that was characteristic of the infants' developmental stage. Thus, this distinction of performatory and exploratory activities appears valuable to understand how infants developed their action systems and perceive new affordances. For example, in a series of experiments, the exploratory activity of children of different ages and abilities were studied in a task requiring them to approach a slope to study whether they perceived the slope as "crossable" or not (Adolph, 1995; Adolph et al., 1997; Adolph, Eppler, & Gibson, 1993; Adolph et al., 2000; Adolph & Eppler, 1998). In these studies, all actions (whether visual or haptic) that occurred before each child passed the edge of the slope were considered as exploratory actions. The possibilities of performatory actions are minimal in young infants as their action systems are not well developed (E. J. Gibson, 1988). Therefore, the distinction between exploratory and performatory action enables description of the links between infants' activity and the attunement of their perceptual-motor system (Adolph et al., 1993; Eppler, Adolph, & Weiner, 1996; E. J. Gibson et al., 1987).

The distinction between exploratory and performatory actions in developmental psychology has motivated studies in the sport of climbing that have investigated the effects of anxiety on affordance perception (Nieuwenhuys, Pijpers, Oudejans, & Bakker, 2008; Pijpers, Oudejans, & Bakker, 2005; Pijpers, Oudejans, Bakker, & Beek, 2006). In these works, the visual fixations and hand movements of climbers have been categorized as being either exploratory or performatory based on the actions utilized to complete the climb. If the action led to a displacement of the climber on the route, it was deemed performatory, otherwise the action was deemed exploratory. Results showed that both exploratory and performatory visual (eye) and haptic (hand) movements increased in high anxiety conditions, suggesting that the climbers performed at a level equivalent to novice performance (Pijpers, 2006). Further to climbing studies, researchers have also differentiated between exploratory and performatory actions in soccer. Specifically, in these works, studies have measured visual exploratory activity (VEA), separate from performatory actions (Jordet, 2005; Pocock, Dicks, Thelwell, Chapman, & Barker, 2019), with VEA defined as head and body movements that are used to scan the environment (pitch, teammates, and opponents) prior to receiving the ball, whereas performatory actions are those observed once a player is in possession of the ball. The differentiation between VEA and performatory action has led to the development of experimental methods that have studied VEA in response to video images presented across multiple screens, without any game-specific performatory action (McGuckian et al., 2019; van Andel et al., 2019). Thus, a methodological consequence of creating a dichotomy between exploratory and performatory actions is that researchers have studied perception and action as two separate processes, which compromises the theoretical view of Gibson (1966). Similarly, in climbing, the differentiation of exploratory and performatory hand movements has been questioned as in many instances, it is possible that movements categorized as being exploratory may actually be “failed” performatory movements (Orth, Button, Davids, & Seifert, 2016). For instance, a climber may have tried to use a handhold, but because the handhold depth was not as expected, he/she may have only touched the handhold, released it, and then used another hold. Thus, even “failed” performatory actions may have temporary performance consequences, they remain important in the process of learning to differentiate information (van Dijk & Bongers, 2014). Thus, during practice, the entire activity (i.e., both exploratory and performatory actions) contributes to their perceptual learning.

In summary, actions have tended to be categorized according to their outcomes: if they enable the performer to reach the task-goal they are performatory actions, otherwise, if they lead to the discovery of available information and preparing the performatory actions, they are related to exploratory activity. Thus, exploratory activity relates to actions that aim at gathering or scanning information before the initiation of a performatory action. Considering the reciprocity of perception and action, the study of prospective control with the distinction between “action to perceive” (exploratory activity) and “action to realize the intention” (performatory action) appears to be in contradiction to the unity of perception-action.

Exploration is Continuous and Multimodal: Exploring is Performing

Exploration Never Ceases

As considered in the previous section, the differentiation between exploratory and performatory actions has contributed important understanding in developmental studies (Adolph, 1995; Adolph et al., 1997, 2000; Adolph & Eppler, 1998), where infants face the task of perceiving whether to act or not (e.g., walking down slopes or walking over an unexpected surface). However, in numerous sports activities, performers are in continual need of adapting their ongoing activity and are, therefore, unable to necessarily stop and “explore” their environment. For example, performance in pole vaulting necessitates that athletes adjust the pole position whilst running at high-speed to accurately point the tip of the pole to the vault box, and then prospectively control when and how to move relative to the pole to convert maximal kinetic energy into gravitational potential energy while avoiding the bar. Indeed, performance environments are often dynamic and require to continuously perceive the opportunities for action relative to ongoing events (Fajen, 2005; Fajen et al., 2008).

The ability to anticipate future states of the individual-environment relation is a characteristic of all animals, especially skilled performers in sport (Araújo et al., 2017). For instance, in a series of recent climbing studies, Seifert and colleagues have found that performers do not appear to perceive the actions enabled by each separate hold during an ascent, but rather, they perceive a chain of movements offered by the properties of the holds and layout on the wall (Seifert, Cordier, Orth, Courtine, & Croft, 2017; Seifert et al., 2018). Moreover, in dynamic environments such as soccer games, players may act by anticipating a chain of actions to score or defend, but they continuously need to probe for potential changes in the ball, teammates, and opponents' movements that could affect the viability of their chain of actions (Dicks, Araújo, & van Der Kamp, 2019). The concept of nested affordances, which emphasizes that seemingly discrete behaviors are better understood as a continuous flow of actions distributed across different temporal and spatial scales, may, therefore, help to understand how individuals efficiently chain their actions to achieve a task-goal.

The concept of nested affordances was further developed by Wagman (2012), who demonstrated the effect of practice on the estimation of reachability, revealing that affordance perception depends on the future states by which a behavior will occur. Specifically, Wagman, Cialdella and Stoffregen (2018) proposed that affordances can be nested in a hierarchy that consists of three levels: the "Why" level, which represents the task goal; the "What" level, which represents the specific behaviors needed to achieve the task goal; and the "How" level, which represents the various means available to achieve the task goal (Wagman et al., 2018; Wagman & Morgan, 2010). For illustration, Wagman (2012) showed that individuals could estimate their maximum touching height (the "Why" level) when they were asked to reach a suspended object (the "What?" level) by (i) standing on toes or standing with heels touching the ground, (a first "How?" level), and/or by (ii) using (or not using) a tool (a second "How?" level). These results indicate that individuals are able to perceive the future state of their action capabilities even when they are about to perform a series of nested actions. Therefore, there is not an exploratory action that dictates what and how to do the next performatory action, but exploration enables performers to keep on accurately perceiving and acting.

In accordance with the nested affordances perspective, we propose that exploration could also be considered as an aspect of performatory activity. For instance, in a team sport such as soccer, the player in possession is not the only sportsperson on the field "performing". All the other players are also acting in such a way that they seek to probe future actions, and at the same time, they move to create opportunities for passes or to restrict opportunities (depending on whether their team is in possession of the ball or not). Thus, performers in team sports are constantly scanning, probing and acting in their environment in such a way that the differentiation between exploration and performatory periods is ambiguous. Moreover, when a performer tries to dribble past his/her opponent, he/she may use deception to influence his/her opponent and guide future actions. That is, as the player is revealing and picking up information, he/she is also generating information. Thus, expertise may reside in the continuous exploratory activity of performers that enables them to maintain an active prospection of the available information to act effectively (Pocock et al., 2019). In sum, the prospective control of action occurs through the information-movement coupling, which enables to continuously adjust the relation between individual and environment to achieve the task-goal (Araújo et al., 2017). On-going actions reveal information that contribute to perception of affordances related to this action (Franchak, van der Zalm, & Adolph, 2010).

Exploration is Multimodal

The continuity of exploratory activity is also dependent on multimodal perception. An important emphasis of James Gibson (1966) was that the environment is not perceived passively in which our actions are responses to stimuli, but that we actively perceive the world through the actions of the different perceptual systems. However, a multimodal account of exploration is lacking in the study of sport skill acquisition. Notably, visual exploration has largely been studied using video-based laboratory tasks where the opportunities for action are severely compromised and not representative of complex sport environments (Mann et al., 2007; McGuckian, Cole, & Pepping, 2018). Indeed, results have revealed that the gaze behaviors utilized by soccer goalkeepers when attempting to save penalty kicks change as a consequence of both the environment (i.e., video presentation vs. real-time opponent) and the response requirements (e.g., simulated movement vs. diving to save the kick) (Dicks, Button, & Davids, 2010).

Comparable to the study of sport performers, the role of exploration in the perception of affordances has also been studied in laboratory tasks, with restrictions placed on participant behavior. For instance, Pepping and Li (2008) investigated the role of visual and haptic exploration on the perception of maximum jumping height from different surfaces. One group of participants was allowed to explore visually and haptically (i.e., they were invited to jump on the different surfaces) whereas another group was limited to visual exploration. Although the haptic exploration group could access more information, they did not improve perception of their jumping capabilities. Rather, they overestimated their capabilities, whereas the participants in the visual exploration group underestimated them. Thus, the results indicate that limiting the perceptual systems during exploration, does not appear to support accurate attunement or calibration. Indeed, methods that have constrained the modes of exploration, have also been used to study the perception of "sit-ability" under different leg lengths (Mark, Balliett, Craver, Douglas, & Fox, 1990), gap "cross-ability" (Mark, Jiang, King, & Paasche, 1999), the "catchableness" of fly balls (Oudejans, Michaels, Bakker, & Dolné, 1996) and the minimum passing height of a barrier when using a wheelchair (Yu, Bardy, & Stoffregen, 2011; Yu & Stoffregen, 2012). In these studies, the limitations on the permitted actions with the different perceptual systems (e.g., notably the haptic system and visual system) has been shown to negatively affect the perceptual judgements of participants in comparison to conditions where they are able to freely explore. Such findings support a multimodal account of exploration and as such, examination of the temporal organization of different exploratory actions provides the opportunity to better understand how multimodal exploration can give rise to skilled perception-action.

Research conducted in the developmental psychology literature has highlighted the necessity of multimodal exploration by showing that the information picked-up through the different perceptual systems is used to support accurate affordance perception. For example, in the "walk on slope" experiment, Adolph and Eppler (1998) revealed that infants can obtain visual information about depth and slant, whilst haptic exploration is required to get information about friction. Furthermore, Adolph, Eppler, Marin, Weise, and Wechsler Clearfield (2000) described the exploratory activity of infants during the "walk on slope" task as a sequential process composed of three modes of exploration: exploration from a distance (e.g., looking at the slope); exploration via direct contact (e.g., touching the slope surface); and exploration of alternative means (e.g., crawling instead of walking). Following this idea of a sequential organization of exploration, Kretch and Adolph (2017) proposed that the mode and organization of exploration in space and time is relative to its cost in terms of effort, time, and injury risk. According to this hypothesis, individuals use the exploration modes following a ramping-up organization process. For instance, haptic exploration is a risky form of exploration because it involves direct contact with an unknown surface, thus, it is only used to obtain new information following less exposed forms of exploration such as visual exploration that can be achieved from a distance and, therefore, with limited risks. Thus, exploratory activity appears to be organized in space and time when individuals search for opportunities for actions. A closer look at how haptic, motor, and visual exploration are linked during tasks is required to reveal the organization and changes in organization of exploration to maintain prospective control during action.

Stoffregen, Mantel, and Bardy (2017) reinforced the importance of multimodal exploration by proposing that perception should be considered as emerging from a single perceptual system rather than from different perceptual systems. This idea follows the global array hypothesis, which proposes that the senses function as a single unit during (active) perception (Stoffregen & Bardy, 2001). Studies have shown that exploratory activity can reveal higher order information to perceive the absolute distance from a target object, which is composed of optic flow patterns and haptic/gravito-inertial stimulation (Mantel, Bardy, & Stoffregen, 2010; Mantel et al., 2015). These results argue in favor of looking for organization in the different dimensions of exploratory activity rather than in isolated perceptual systems. For instance, affordance perception depends on information exploited by the eyes, head and whole-body in motion, as studies have shown that eye-height information is important for calibration of the perceptual system to perceive whether one can sit on a seat or fit through a doorway (Franchak et al., 2010; Mark, 1987; Mark et al., 1990). The information-movement couplings utilized during exploration may, therefore, provide individuals with the ability to act purposefully to reveal information. Subsequently, the usefulness of the revealed information depends on the organization of individuals' exploratory actions. Thus, exploratory activity is not only an information-gathering activity that occurs before the start of performatory actions, but it is embedded throughout the entirety of a performer's activity. Exploration is multimodal as individuals do not perceive the environment through isolated perceptual systems, but as a whole. From this whole, individuals must find functional patterns to discover affordances, which is made possible through attunement and calibration of the perceptual-motor system. But how can performers become sensitive to properties of their performance environment? How does exploration evolve with practice and experience in a task?

Exploration During Practice: Learning to Reveal Information

Dynamics of Exploration: Toward Less Exploration with Practice?

When exploration is investigated as a sequence of information-gathering actions, research has shown that exploratory activity tends to decrease with practice, and performatory activity also decreases as individuals attune to more reliable information and become more skilled in the task (e.g., Seifert, Boulanger, Orth, and Davids 2015). Quantification of exploratory actions has been studied during climbing, within which participants were instructed to climb three different routes - with different orientations of handholds – as fluently as possible (Orth, Davids, & Seifert, 2018; Seifert et al., 2015). In these studies, the handhold orientation in the climbing route and experience of participants in the task impacted the amount of exploration of climbers. Specifically, the number of exploratory actions decreased with practice and increased with the complexity of behavior specified by the climbing routes. Similar findings have been observed in the development of tool creation (van Dijk & Bongers, 2014). In this study, van Dijk and Bongers differentiated between distinct periods during task completion: (i) a visual phase; (ii) a manual and visual exploration phase; and (iii) a construction phase. The first two phases were considered as exploratory activity while the construction phase was related to performatory activity. The distinction between the exploratory and performatory periods was defined relative to the initiation of a movement that was aimed at achieving the task (i.e., to create and use a tool with the pieces provided). The duration of the two exploratory periods decreased with practice, whilst actions during these phases were found to be more goal-directed, as the actions were oriented towards constructing the final tool. The authors concluded that actions became more goal-directed with the attunement of the participants to their environment and the discovery of new possibilities for action. In sum, these findings suggest that the amount of exploration decreases as the performers become better attuned to relevant information about affordances.

However, focusing analysis solely on the amount of exploration may be misleading. For example, Wagman, Shockley, Riley and Turvey (2001) examined how the accuracy of participants' estimations of the width and height of different objects differed following periods of haptic exploration completed under different modes of practice (i.e., with or without knowledge of results). Results revealed that irrespective of the feedback received, exploration time and exploration complexity (e.g., randomness in hand movements) decreased, which suggests that exploration decreased and gained in goal-directedness (cf. van Dijk and Bongers 2014). Nevertheless, attunement did not occur for the groups without knowledge of results; in this case, the decrease in exploration time was not associated with improved performance in the size estimation of objects. This finding is in line with infant locomotion studies, which have reported that neither the amount nor the type of exploration predicts motor decisions (Adolph et al., 2000; Joh & Adolph, 2006; Kretch & Adolph, 2017). Therefore, an increase in the effectiveness of exploration cannot be explained solely through the measurement of the quantity of exploration; a measure that accounts for the accuracy of perception is required.

The literature considered in this section suggests that individuals who become successful in a task do not necessarily decrease the quantity of exploration over time. Rather, it appears that successful exploration reveals the opportunities for action that fit both an individual's action capabilities and properties of the environment. Thus, successful exploration guides the pick-up of reliable information for task accomplishment; that is, successful exploration is a consequence of increasing accuracy rather than decreasing quantity. Thus, we argue in the following sections that when studying the perceptual learning processes of attunement and of calibration, it is more insightful to investigate changes in performers' exploration during practice rather than the volume of exploration.

Explore to Reveal Reliable Information: Differentiation of Information

Perceptual learning studies have demonstrated that, with practice, novices can learn to exploit more reliable informational variables through the attunement of the perceptual systems (Jacobs & Michaels, 2006; Smith, Flach, Dittman, & Stanard, 2001; van der Kamp, Savelsbergh, & Smeets, 1997). To better understand the relation between exploration during learning and task achievement, an important question is whether the changes in the pick-up of information are a consequence of changes in the mode of exploration. For instance, van Dijk and Bongers (2014) observed the functional reorganization of gaze behavior with practice in their tool making task. This reorganization had both an exploratory role, which led to the pick-up of information about affordances, and a performatory role, which led to alterations of the environment that led to the discovery of new affordances. Given the mutuality of perception-action, changes in the information exploited may be assessed by the changes in the way individual interacts with the environment. For example, Withagen, Kappers, Vervloed, Knoors and Verhoeven (2013) investigated if sighted, and blind children and adults were using the same exploratory actions to differentiate between dimensions of an object including the shape, weight, volume and texture. The experimenters defined five exploratory procedures that they used to code the participants' hand movements. They measured the percentage of time spent using each exploratory pattern and the quality of exploration (i.e., the time needed before an estimation). Results showed that specific exploratory patterns were necessary to estimate some dimensions of the objects and that the difference between sighted and blind participants was not a result of the specific exploratory pattern utilized but in the quality of exploration (i.e., blind participants needed less time to respond). With practice, participants learnt to differentiate three out of four object dimensions (i.e., their shape, texture and volume but not their weight), which illustrated that practice led to the detection of more reliable information. Thus, the novice participants needed to find an adequate means of exploration to interact with the objects to achieve the task and, as such, they learnt how to explore.

Wagman (2012) pointed out that changes in exploratory actions can be obvious (e.g., like touching a surface to estimate its walk-ability after a fall, Joh and Adolph, 2006) or more subtle (e.g., changes in head and torso motion are sufficient to judge maximum sitting height when action capabilities are changed: Stoffregen, Yang, and Bardy, 2005). In accordance with different contemporary learning perspectives in ecological psychology (Fajen, 2005; Jacobs & Michaels, 2007), it would be important to understand whether differences exist in the modes of exploration associated with changes in perceptual attunement and the calibration of action. An example of an obvious change in exploratory activity was observed in a study by Joh and Adolph (2006) during which, children had to walk on a path with a hidden foam pit. Results showed that after falling in a trial, children increased the amount of exploration on subsequent trials: they took more time before walking on the path, they changed their locomotor behavior, and they increased the use of exploratory touching near the foam pit. Task achievement was due to the differentiation of reliable visual information (i.e., the delineation of the new ground surface), which was motivated by a fall in an earlier trial that guided changes in the exploratory and locomotor activity. Exploration may lead to misperception and failure in the task if the exploited information is not reliable, irrespective of the time spent exploring the environment (Adolph, Marin, & Fraisse, 2001). Therefore, the quantity of exploration during learning should be investigated alongside the mode of exploration (i.e., how do individuals reveal information to achieve the task?) and the dynamics of exploration during practice (i.e., what were the previously observed outcomes and behaviors?).

A recent climbing study proposed an innovative method to study the dynamics of exploration during the acquisition of a complex motor skill. To describe the temporal organization of exploration of climbers during practice, Seifert, Orth, Mantel, Boulanger, Hérault, and Dicks (2018) defined five different climbing states: (i) looking at the route; (ii) adjusting the center of mass; (iii) determining which hold to use (i.e., modifying the position or orientation of the hand or foot); (iv) hold changing (i.e., grasping another hold while the hip stays stationary before motion); and (v) moving the hip and at least one limb. The number of times each mode was used, and their relative duration was measured for each trial during practice. The authors presented the dynamics of exploration across multiple temporal levels, which enabled improved understanding on the relations between exploration during learning and task achievement. Their results revealed that climbers decreased the number of stationary states while their climbing fluency increased, suggesting an improvement in “route finding” skill, encompassing the ability to perceive a chain of movements (i.e., nested affordances) on the climbing route. Such association between the dynamics of exploration and the dynamics of performance highlights changes in the efficiency of an individual’s exploration. The analysis of the dynamics of the efficiency of the exploratory activity would also reveal if the learning protocol enabled individuals to learn to explore effectively, that is by guiding performers toward information about affordances relevant for the task achievement.

Explore to (Re)Calibrate the Perceptual-motor System: Scaling Action to the Information

Although the previous section stressed that the exploration of performers may change as they increase their sensitivity to their environment, it shouldn’t be forgotten that the accurate perception of affordances is grounded in the individuals’ sensitivity to their action capabilities (Fajen, 2007). For example, Oudejans, Michaels, Bakker, and Dolné (1996) used an interception task to study the "catchableness" of a fly ball. To be perceived, this kind of affordance requires that participants scale information to their body size (e.g., eye height and leg length) and to their running and catching capabilities. Results revealed that participants were more efficient in judging the ball "catchability" when they could move than when they stood before giving their judgement. This difference was explained by the availability of information about the boundaries of the participants action capabilities when they are moving, which supports the view that exploration is continuous.

Given that action capabilities are liable to change due to motor development on a longer timescale, and on a shorter timescale, due to fatigue, calibration and recalibration must be continuous to accurately perceive opportunities for action (Franchak & Somoano, 2018). More specifically, a change in action capabilities modifies the mapping between information and action which requires recalibration, that is, to adapt the scaling of action to information (van Andel, Cole, & Pepping, 2017). Moreover, Brand and de Oliveira (2017) proposed that the exploration required for recalibration depends on the availability of reliable information and on the magnitude of the disturbance of the action system. The authors subsequently suggested that expert performers may better adapt to disturbances in their action capabilities as they may have developed exploratory actions that support recalibration over a relatively short timescale (Brand & de Oliveira, 2017). For example, Mantel, Stoffregen, Campbell, and Bardy (2015) demonstrated that individuals could generate sufficient information about the distance between themselves and an object with only a combination of eye, head and torso movements. Such adaptive exploratory actions could reflect the subtle changes in exploration that we previously discussed that are used to adapt perception and action to the context (Wagman, 2012).

During development, children adopt different locomotion patterns including crawling and walking due to postural milestones (e.g., learning to crawl, to walk…), which requires calibration of an infant's action capabilities and contributes to the process of differentiation of information (Adolph et al., 1997; Adolph & Eppler, 1998). Indeed, experiments on the slope crossing task have revealed that infants in their first weeks are unable to judge risky slopes. Rather, they needed weeks of locomotor experience to develop exploratory activity to generate information that reveals the fit between environmental properties and their capabilities (Adolph, 2008). In fact, the emergence of new coordination modes can increase individual action capabilities and extend the field of possibilities that the environment offers to individuals. During learning, changes in patterns of coordination used to achieve task outcomes have been observed during practice (Chow et al., 2008; Komar et al., 2019; Nourrit et al., 2003). These behavioral dynamics may induce the need for learners to modify their exploratory activity to control their movements accurately, but it also gives to the learners the chance to discover new opportunities for interaction with the environment.

It has been suggested that the discovery of original and functional possibilities for action (i.e., individuals' creativity) may be enhanced when individuals act close to their maximal action capabilities (Orth, van der Kamp, Memmert, & Savelsbergh, 2017). Conversely, it has been proposed that in everyday tasks, individuals tend to stay in a safe region in-between the boundaries of their action capabilities to preserve the possibility to adapt their behavior (Fajen, 2005). For instance, studies show that children playing in a climbing playscape stay within a safe region of their action boundaries and keep a security margin when they climb (Croft, Pepping, Button, & Chow, 2018; Prieske, Withagen, Smith, & Zaal, 2015). This protective behavior has also been observed in a virtual car braking task where participants anticipated braking even if they could stop later (Fajen, 2005; Fajen & Devaney, 2006). However, in competitive sport contexts, performers are pushed toward their action boundaries. In such instances, exploratory movements (i.e., like touching a hold in a climbing task to estimate its grasp-ability) may be limited so that performers are targeted in their exploration to maintain a prospective control and to perceive the limits of their action capabilities. For example, when attempting to save penalty kicks, soccer goalkeepers tend to initiate movements to intercept the ball outside of their action boundaries (Dicks, Davids, & Button, 2010). Although this late dive may not enable goalkeeper to reach for the ball if the shot is highly accurate, this timing of action allowed goalkeepers to rely on more useful spatial information to anticipate kick direction. Thus, methods that investigate affordance-based control of action should assess the maximal action capabilities of the performers to examine whether they are sensitive to their action boundaries. Also, it seems that performers should explore a large range of their action capabilities during practice to develop efficient exploratory activity, and acting close to their action boundaries may encourage performers to find new movement solutions that would extend their maximal action capabilities and their possibility of exploration.

Learning to Explore

A key emphasis of this critical review is that skill learning conditions in sports should encourage the development of modes of exploration that reveal the fit between environmental properties and performers' action capabilities to perceive affordances relevant for task achievement. Practice conditions should: (i) lead performers to develop exploratory activity that reveals more reliable information; and (ii) encompass safe environments where performers can learn to explore even when they behave close to – and beyond - their current maximal action boundaries. When applied to climbing, a safe environment refers to situations from which the learner can escape, fallback or adapt and use a back-up plan. To test this hypothesis, Seifert, Boulanger, Orth, and Davids (2015) designed three climbing routes by manipulating the hold orientation and the number of available edges for grasping during learning. A horizontal-edge route was designed to allow horizontal holds in which the trunk faced the wall. A vertical-edge route was designed to allow vertical holds, which experienced climbers were able to grasp with the side of their body toward the wall. Finally, a double-edge route was designed to invite both horizontal and vertical holds. Because a route with only vertical-edge holds was challenging for novice climbers, the double-edge route allowed safe and functional exploration because climbers could both exploit their preexisting behavioral repertoire (i.e., horizontal-hold grasping pattern with their trunk toward the wall) and explore new behaviors (i.e., vertical-hold grasping with their side toward the wall). The results indicate that this safe environment of practice can be useful because perceptual-motor exploration appears less risky, with possible back-up and the learner is more inclined to experiment in these regions (Seifert et al., 2015). Thus, this learning design guided the exploration of learners to search for reliable information to perform the vertical-hold grasping.

However, research has also demonstrated that if there is insufficient variation in the practice environment, learners can sometimes exploit information that does not support accurate perception when they are exposed to a broader range of situations (Fajen & Devaney, 2006; Smith et al., 2001). To address this issue, Smeeton, Huys and Jacobs (2013), proposed a novel type of intervention to guide learners' exploration to pick-up more reliable information by neutralizing less useful information. More specifically, they reduced the usefulness of the informational variables that were potentially used by novice tennis players to anticipate the direction of their opponent's stroke by keeping constant this potential information while the strike outcomes were varied. Two important findings revealed that: (i) learners exploited new information if the usefulness of the initial information is reduced; and (ii) learners could attune to higher order information that supported accurate perceptual-motor skill in both a post-test and transfer test (in this study, the higher-order information was distributed across different body parts of the opponent).

Variable practice has been proposed to guide learners' perceptual attunement and to enhance transfer of learning (Fajen, 2005; Fajen & Devaney, 2006; Huet et al., 2011). In this form of practice, less useful informational variables are varied across practice trials so that learners are forced to search for new and more consistent information to guide their action. Smith, Flach, Dittman, and Stanard (2001) proposed the concept of flexible attunement to describe the ability of learners to rely on different informational variables according to the performance context. Fajen and Devaney (2006) observed such flexible attunement while comparing the effects of different variable practice conditions to perform a braking task in a virtual environment. They manipulated either (or both) the stop sign radius and/or the initial speed of the virtual vehicle so that the less reliable informational variables, like the expansion rate of the sign would no longer be useful. Results showed that these interventions led to perceptual attunement: participants learnt to rely on high order informational variables to guide their actions. Similarly, Huet, Jacobs, Camachon, Missenard, Gray, and Montagne (2011) created a flight simulator where the less reliable informational variables initially used by novice participants were varied so that exploiting this information no longer supported accurate action. Results showed that participants in the variable practice group outperformed a constant practice group in a transfer test due to changes in the informational variables used to guide action. Developing interventions that support flexible attunement (i.e., transfer in the use of a variable to guide action) is important in sports given the variable and complex nature of sport environments (Fajen et al., 2008). Dicks, Pocock, Thelwell, and van der Kamp (2017) proposed a form of on-field variable practice to train goalkeepers in a penalty task. The goalkeepers faced three players that started their run-up together but only one them executed the penalty on each trial. This intervention was aimed at directing the goalkeeper's attention to information that emerged around the time of when the penalty taker's foot contacted the ball. Compared to constant practice (i.e., facing penalty kicks from one player executing the run-up and penalty), the intervention enhanced performances of goalkeeper on non-deceptive penalty kicks, which may be due to a better perceptual attunement. Such intervention must be developed to help learners to pick-up more reliable information about affordances, and so that the exploration developed during practice can be transferred and used to achieve high performances outside the training context.

Linking perspectives from ecological psychology to existing findings on the dynamics of learning may help to better understand the transfer of perceptual-motor skills to multiple contexts of performance and to inform interventions that both develop a performer's motor repertoire and guide learners toward more reliable information. Indeed, a large volume of the literature focusing on interventions in performance contexts is rooted in the dynamical systems approach to learning (Schöner et al., 1992). This framework has focused on the effect of the interventions on coordination dynamics (i.e., the motor repertoire of the learners) rather than on perceptual attunement (Chow et al., 2008, 2007; Lee et al., 2014). Based on Bernstein's (1967) observation that practice is a form of "repetition without repetition", interventions have focused on the role of movement variability to develop the adaptability of learners. For instance, training interventions such as "differential learning" have proposed to add random noise to task constraints (i.e., irrelevant movement components) to increase the performance of learners by discovering multiple movement solutions (Schöllhorn et al., 2006; Schöllhorn, Hegen, & Davids, 2012; Schöllhorn et al., 2009). A question remains about the qualitative nature and actual relevance of the induced variability (i.e., the random noise in the task constraints). Indeed, variations in the learning contexts may encourage attunement only if reliable information is available in the different learning conditions (Smeeton, Huys, et al., 2013). Cardis, Casadio, and Ranganathan (2018) have also pointed out that such variability may increase exploration of new solutions but may adversely affect the ability to retain the learned solution, thus, they questioned the threshold of variability after which variable practice impairs learning.

In summary, learning interventions may promote the discovery of exploratory actions that enhance the transfer of perceptual-motor skills. Learners should be given the opportunity to safely explore and to be guided toward more reliable information for action. Reducing the usefulness of the less reliable information seem to be effective in enhancing transfer of learning. In this aim, the less reliable information can be neutralized or varied across practice trials so that learners search for new and more reliable information for action. However, care must be given to the context of practice that may limit the opportunity to interact with the environment. Thus, as learning is not about accumulating information across trials but rather generating and exploiting useful information for action, interventions must lead performers to learn to explore rather than learning a model of skill.

Conclusion

This critical review focused on how exploratory activity can support the development of perception-action during learning. We considered that exploration is continuous and multimodal, and so, the generation and pickup of information lies in all the actions of performers. Therefore, we propose that future investigations in skill acquisition should look at the changes in the organization of the learners' exploratory activity in relation to performance achievements rather than observing the amount of exploration during practice. Experts in high-performance contexts such as sport manage to perceive future states of their relationship with their environment even though they experience changes in their action capabilities or events. Therefore, a dynamic view of exploratory activity may reveal how experts in sport act in uncertain and dynamic environments. Practice conditions must lead individuals to adopt exploratory activity that reveals the fit between the environmental properties and their action capabilities. Moreover, to discover new opportunities for action, learning environments should promote safe conditions that give performers the opportunity to develop exploratory activity, even when they act outside of a 'safe region' of their action capabilities. In this regard, interventions that guide learners to search for more reliable information appear to be the most suitable learning design to develop exploratory activity that would enhance the transfer of skill to various performance contexts.

Chapter 2: Eye Movements in Skill Acquisition

Introduction

In sports and exercise, most of the literature on gaze behavior focused on decision-making skills. As highlighted by reviews on the topic, these studies were mainly performed in laboratory settings with participants facing a screen and having artificial or limited opportunities for movements (Kredel, Vater, Klostermann, & Hossner, 2017; Mann et al., 2007). However, such experimental settings were shown to bias the gaze behaviors as eye movements were shown to be tightly linked to the action requirements (Dicks, Button, et al., 2010). And even when the action requirements are similar to a real-world situation (e.g., cycling on a stationary bike in a laboratory and cycling on a road), the decrease in task complexity affects performers' gaze behaviors (Zeuwts et al., 2016).

The links between gaze behaviors and body movements were mainly studied in discrete sport skills and were often restrained to the quiet eye properties (i.e., the period between the onset of the final fixation and the action, Vickers, 1996) as gaze behavior in such context is more easily captured in relation to key instants of the movement skills (e.g., the release of the ball in basket-ball jump shots, Klostermann, Panchuk, & Farrow, 2018). More complex examinations of the link between eye and body movements were also performed, such as in three balls cascade juggling (Huys & Beek, 2002; Huys, Daffertshofer, & Beek, 2003) and more recently in summersault with full twist (Natrup, de Lussanet, Boström, Lappe, & Wagner, 2021). Such examinations of the link between gaze behaviors and body movements are promising to improve the understanding of how performers pick-up information to control their action (Dicks, Button, Davids, Chow, & van der Kamp, 2017; Navia, Dicks, van der Kamp, & Ruiz, 2017).

However, in numerous activities, actions are embedded one into another. Notably when performing discrete actions such as object manipulation during locomotion. For instance, most of the team sports involve the control of an object (generally a ball) while moving on the pitch to use space (and time) optimally. These activities are performed in complex environments from which performers need to effectively pick up information to make relevant decisions while manipulating objects appropriately, as in team sports. In experimental settings, the complexity of both the environment and the action requirements were importantly reduced with laboratory tasks and virtual displays to investigate performers' decision making and pickup of information (Mann et al., 2007; McGuckian, Cole, & Pepping, 2018). On another side, when naturalistic protocols were used, they focused on head movements to examine visual exploratory activity (e.g., Jordet, Bloomfield, & Heijmerikx, 2013; McGuckian, Cole, Jordet, Chalkley, & Pepping, 2018). The lack of naturalistic investigations of eye movements in relation to action in such environments is partly due to the technological limitations of the eye-tracking technology. It is relatively recent that wearable devices enable the capture of the eye movements while letting performers freely moving (although the use of such system is still not advised in sports involving contacts for performers' security, device integrity and data collection validity). A recent study originally proposed an exploratory analysis of football players' gaze behaviors during a football game showing that opportunities arise to account for more naturalistic conditions (Aksum, Magnaguagno, Bjørndal, & Jordet, 2020).

Finally, the great majority of studies investigating gaze behaviors in sports relied on cross-sectional study design comparing novice to skilled performers. The use of such method implied that the transition from novice to skilled coordination between eye and body movements was straightforward, inferring that novices should be guided toward the "optimal" gaze behavior of the skilled performers (Dicks, Button, et al., 2017).

Therefore, this review aims to highlight the importance of the coordination between the eyes and the body movements to effectively perform goal-directed behaviors in complex environments. First, we will present the anatomical structures of the eye that explain the distinction between central and peripheral vision. This presentation aims to emphasize why the analysis of the gaze behaviors is relevant for the study of the visual control of action. Second, we will review the movements of the eye and the head that are used by humans to visually explore their surroundings. Indeed, when performing in natural tasks, visual information needs to be actively obtained, but this activity is not limited to the eyes and requires the coordination of different body structures. Third, we will review the studies linking eye movements and the control of action with a particular emphasis on locomotion tasks. This review will highlight the dual demand constraining the visual system in such tasks. And finally, we will highlight the promises of longitudinal study design to understand the coordination between eye and body movements to better understand skill acquisition in sporting tasks involving locomotion.

The Structure of the Eye

The link between visual information and action in sport skills is often studied without analyzing the gaze behaviors. For instance, coordination patterns can be compared when they are performed in the dark or with light (e.g., Bardy & Laurent, 1998) or visual exploration can be examined with the performers' head movements (e.g., McGuckian, Cole, Chalkley, Jordet, & Pepping, 2019). However, we argue that these manipulations considerably simplify the information pickup behaviors and remove information about the cues on which participants rely to guide their actions. Nonetheless, we will also see that the gaze location does not reflect the whole visual information that performers obtain. Thus, the following part presents the bases of the eye functioning to better understand what is obtained though the gaze.

The light from the environment is refracted by the lens and the cornea so that light converge on the retina. Due to its elastic properties, the lens shape can be modified by the ciliary muscle to adapt the light refraction on the retina (**Figure 1**). The contraction of the ciliary muscle acts as a sphincter, which when activated bulge the lens, increasing the curvature of the lens surface. This function enables to have a clear picture of the object projected on the retina according to its distance from the eye. This function is called accommodation.

The amount of light going into the retina through the pupil is controlled by the iris. This tissue acts as a diaphragm. This function is assured by two antagonist pupilar muscles: the sphincter and the dilatator muscles which respectively reduce and increase the diameter of the pupil, thus the amount of light reaching the retina.

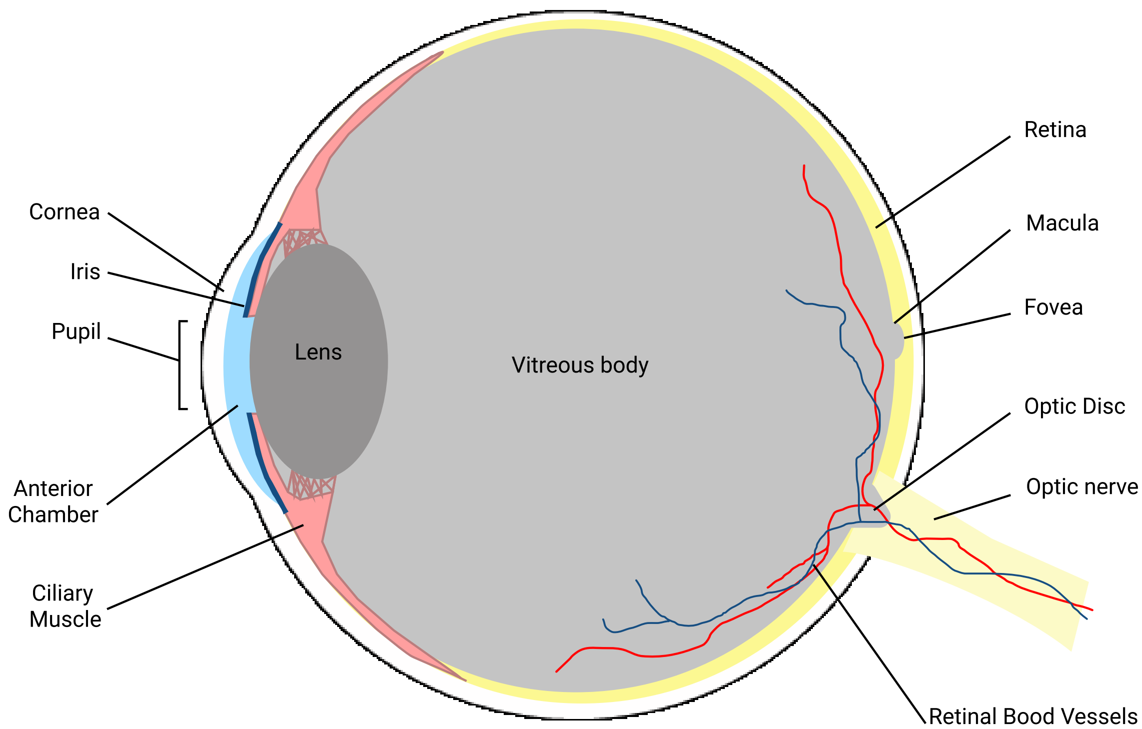

Figure 1. Anatomy of the eye.
This schema represents a transverse cut of the right eye viewed from above.

Two kinds of photoreceptors can be found on the retina: the cones and the rods. The cones enable the perception of colors, shapes, and a better optical resolution. The rods have a lower light threshold which facilitates night vision and the detection of movements. These photoreceptors are not uniformly located on the surface of the retina. A small depression at the center of the retina (in front of the pupil) forms the macula which contains at its center the fovea. The macula possesses the highest density of cones. Then, the rest of the retina is dominantly composed of rods and the density of photoreceptors decreases as the distance from the fovea increases. This repartition of the photoreceptors explains the differences in terms of visual acuity between the foveal vision (also called central vision) and the peripheral vision. It also explains that, although foveal vision has the best resolution, it represents a very narrow area of our visual field (**Figure 2**, about 2° of visual angle, corresponding to the width of the thumb at arm's length, O'Shea, 1991). The remaining of our visual field (i.e., the peripheral vision) shows a decreasing resolution as the distance from the center of the foveal vision increases. Also, the visual field possesses a blind spot at about 15° laterally from the fovea (**Figure 2**). This blind spot corresponds to the location of the optic disc on the retina, where the optic nerve connects to the eye.

Thus, the structures of the eye seem to favor the obtention of a clear picture from the foveal vision, which we try to capture experimentally through the gaze point. The gaze point represents the location in the environment from which the observer obtains the highest acuity. However, peripheral vision is still sensitive to movements. Thus, the examination of the gaze behavior informs how visual information is retrieved from foveal and peripheral vision.

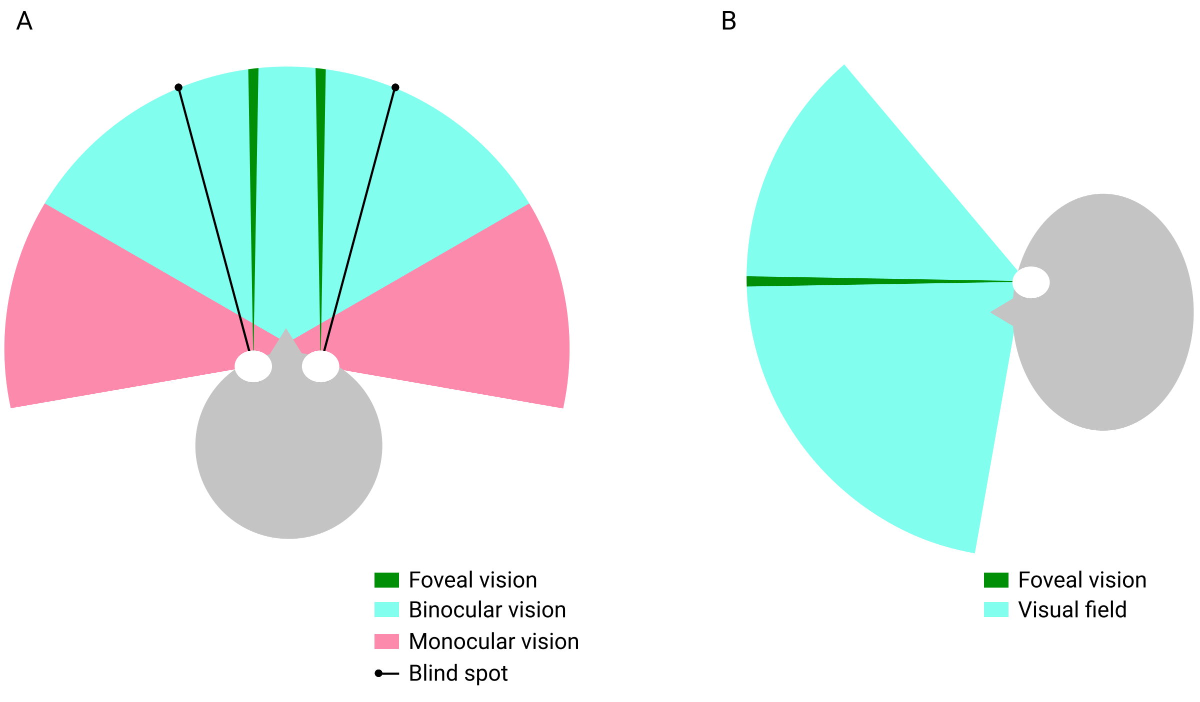

Figure 2. Horizontal (A) and vertical (B) visual field in human.

The Eye Movements within and with the Head

The eye movements are characterized by periods of (relative) immobility and periods of fast movements relative to the head. These two events are termed as fixations and saccades, respectively[1]. The studies in sport science mainly focus on the location of the gaze point during fixations to quantify the time that participants spend fixating different cues from their environment while performing (or before making decision in laboratory settings) (Kredel et al., 2017; Mann et al., 2007). This high interest in fixations can be explained by the fact that during fixations, the object toward which the eye is directed appears in the foveal vision and thus, in the area of the visual field from which the resolution is at its maximum. The saccades, however, induce the loss of the visual information during these fast movements (although, this affirmation is under discussion, see Binda & Morrone, 2018). Visual information is also lost when the eye is blinking, which has the function to clean the cornea and protect the eye in case of change in light intensity or when an object is approaching. Seminal studies of these eye movements in natural settings (e.g., preparing a tea and making a sandwich, Land, Mennie, & Rusted, 1999 and Hayhoe, Shrivastava, Mruczek, & Pelz, 2003) showed that (i) fixations were rarely task-irrelevant as the eye was generally directed toward objects that were useful for the task (although they were not the most salient in the visual field), (ii) the observers rarely fixated their own hand but rather the part of the object they wanted to grasp and (iii) fixations were performed "just-in-time" as suggested by the temporal proximity between fixations and actions (Hayhoe & Ballard, 2005; Land, 2009).

Then more complex eye movements can be observed when observers fixate moving objects or when observers are moving. For instance, smooth pursuit enables to track with foveal vision an object moving relatively to the observer, but if the movement speed is too high, the eye movements become more saccadic. This is for example the case in cricket or baseball where batters cannot track the high speed of the ball (Kishita, 2006; Land & McLeod, 2000). In cricket, a seminal study showed that performers made a predictive

[1] There is a high variability in the methods used to identify fixations and saccades. Salvucci and Goldberg (2000) even proposed a taxonomy of the algorithm-based methods used to identify fixations. This diversity in the methods led to confusions in the definitions of these events (Hessel et al. 2018). Thus, we referred to fixations in terms of stillness of the eye relatively to the head, but fixations may also be defined as stillness of the point of gaze in the environment, which, in case of displacement of the observer, implies movement of the eye.

saccade toward where the ball would bounce and then track the ball with a smooth pursuit (Land & McLeod, 2000). When the object is moving toward the observer, the eyes move in opposite direction to maintain binocular vision while accommodating to the changing distance: this movement is called vergence.

Other eye movements were also observed in sport contexts and were characterized by particular gaze displacements. These gaze behaviors suggest that peripheral and foveal vision are used conjointly when multiples cues and objects are monitored to limit the number of saccades, thus, the loss of visual information (e.g., foveal spot, gaze anchor, visual pivot, this topic is addressed directly in Klostermann, Vater, Kredel, & Hossner, 2020). For example, a study comparing expert and intermediate jugglers showed that experts made smaller gaze movements than intermediate jugglers and their gaze behavior adapted to the tempo of the juggling, adaptation that was absent in intermediate jugglers (Huys & Beek, 2002). The authors also examined the coordination between gaze and ball movements and showed that intermediate jugglers tended to track each ball movements vertically (i.e., a 1:1 frequency coordination between gaze and ball movements) whereas experts could perform juggling with one gaze movement every two ball movements (i.e., a 1:2 frequency coordination between gaze and ball movements). According to the authors, these results suggest that with expertise, jugglers rely more on peripheral vision to control their movements as they perform fewer eye movements than intermediate jugglers (who used more smooth pursuits and saccades) by maintaining their gaze at proximity of the peak of the balls trajectory, which can be compared to a gaze anchor (Huys & Beek, 2002).

When objects are moving with a large angle in the visual field or when relevant cues are all around performers (e.g., the opponents and teammates in team sports), observers may also need to turn their head to obtain visual information. The eye can compensate the head turn to fixate objects during the head turns. This is called the vestibulo-ocular reflex as the coordination of the eye with the vestibular system enables the eye to move in the opposite direction of the head to maintain the gaze toward an object in the environment. This eye-head movement illustrates that the vision is not isolated in sensory terms as it is well coupled to the vestibular system, but also in motor terms as eye movements are here coordinated with the head motion (Land 2004). In the study about the eye movements during juggling, the authors also proposed that experts probably relied on more haptic and kinesthetic information than intermediate jugglers (Huys & Beek, 2002). This complex relation between the visual system and other sensory systems is also discussed elsewhere (Land, 2009).

As illustrated by the vestibulo-ocular reflex, the visual field is constrained by the head motion and orientation. Each head movement modifies the visual field so that by only moving the eyes and turning the head, observers can look at what is happening behind them with monocular vision (the eye can move up to 100° laterally and the head rotations are up to 180° from side-to-side, **Figure 2**). Although eye saccades are sufficient to make small gaze shifts (e.g., when watching a screen), larger amplitudes of gaze displacements require the eye to move in a coordinated manner with the head. For example, because of their position on the pitch, football midfielders are more likely to receive the ball from defenders behind them but must look for action opportunities to move the ball forward on the pitch, which demands that they perform head movements to locate in their surroundings opponents, teammates and free spaces (Jordet et al., 2013). This scanning behavior was considered in the study of footballers' visual exploratory activity (VEA) using video analysis or more recently, using inertial measurement unit placed on the footballers' head (Jordet, 2005; McGuckian, Beavan, Mayer, Chalkley, & Pepping, 2020; McGuckian, Cole, Jordet, et al., 2018). These studies showed that footballers who performed more scanning movements made faster decision when in possession of the ball and were more likely to pass the ball forward. The VEA also differs in relation to playing role and phase of play (McGuckian, Beavan, et al., 2020; McGuckian, Cole, Chalkley, Jordet, & Pepping, 2020). They also showed that the VEA changed when the time from ball reception approached, suggesting that exploratory behavior is performed differently when players search for opportunities for action, or when they are about to control the ball (McGuckian, Cole, Jordet, et al., 2018; van Andel et al., 2019). A limitation of these studies is that they did not examine the eye movements, which limits the identification of the cues used by performers (i) to navigate effectively on the pitch, (ii) to control actions with the ball and (iii) to make effective decisions. Also, the displacements of the performers are not considered although the VEA is embedded within the performers' movements on the pitch. Indeed, many sports involve making decision and interacting with the surroundings (e.g., objects or other performers) while concurrently navigating in the performance space. Thus, locomotion plays an important role in performance and constrains visual exploration but is often not taken into account in study design.

The Eye Movements during Locomotion: Timing of Information Pick-up

The visual field is constrained by the whole body. First, by its posture and height, as depending on eye-height, visual information is modified. Eye height is important in different situations, such as controlling a vehicle (e.g., car, plane, bicycle). For example, a study showed that varying pilots' eye-height affects the reliability of informational variables to specify a plane approach angle to runway (Huet et al., 2011). At the developmental timescale, the visual field of human evolves in relation to body growth and change of posture (Franchak, 2019; Kretch, Franchak, & Adolph, 2014). When crawling, eye-height and head orientation constrain infants to mostly look at the ground at proximity of their hands, whereas when they are walking, distal information becomes much more available (Kretch et al., 2014).

These changes in terms of eye-height during the development of locomotion also affect the information-movement coupling of infants, as shown by the specificity of learning observed in sitting, crawling and walking: in new postures, infants attempted to perform impossible actions (i.e., crossing gaps) that they knew they could not perform in the previous posture (Adolph, 2000; Adolph et al., 2000). In sporting contexts, the body postures are also important for the pickup of visual information. Regarding the previously described example of the football midfielder, the body orientation adopted before the reception of the ball can ease (or harden) the players' VEA. When the midfielder is directly facing the ball, looking backward for a potential opponent and/or teammates demands large-amplitude head movements with large portions of the visual field covert with monocular vision. However, if the midfielder adopts a posture with the shoulders more laterally oriented, the head movements in direction to the opposite goal are more easily performed and can be looked at with the two eyes (**Figure 2**). Of course, the counterargument is that in this new position, the blind side is moved.

The study of the visual control of locomotion yields questions about sport skill acquisition in dynamic and complex environments. First, studies in perceptual-motor development questions how the use of peripheral vision would evolve with practice in sport context. With the development of locomotion, avoidance of obstacles can be performed with more reliance on the peripheral vision, as infant walkers were more likely to fixate obstacles than adults to overcome them, while adults and children rather fixated obstacles from about three steps away (Franchak & Adolph, 2010; Franchak, Kretch, Soska, & Adolph, 2011). However, navigation in environment with obstacles could be achieved flexibly by both children and adults by relying only on peripheral vision or using foveal vision in addition (Franchak et al., 2010). Thus, if these findings apply to the learning timescale, sports performers may rely more on peripheral vision with practice to control their navigation, however, some discrete actions may still require foveal vision.

Examination of where to look was made in other locomotion tasks. A seminal study investigated the gaze behavior in car driving (Land & Lee, 1994). The results showed that the gaze direction relative to the car's heading was similar to the wheel steering angle during the recordings. During bends, the gaze was directed toward the "tangent point" on the inside of the bends. This tangent point appeared to be informative about the curvature of the road. The eye movements gave direction to the car in the bends as saccades to the tangent point were performed 1-2s before entering the bends (Land & Lee, 1994). This link between where the visual system is oriented and the direction of the vehicle was also found in racing drivers during high speed practice (Land & Tatler, 2001). In speed skating, examination of elite and near-elite athletes showed that elite athletes directed their gaze toward this "tangent point" more than the near-elite athletes during turns, which affected positively their skating speed (Vickers, 2006). Adversely, directing the gaze toward the outside lines or lanes was negatively correlated with lap times, suggesting that being able to maintain or increase speed in turns is dependent on gaze direction during performance (Vickers, 2006).

In cycling, Vanteenkiste et al. (2013; 2014; 2017) performed a series of studies showing that gaze behavior was sensitive to multiple constraints such as the road quality, the path width and the riding speed. These studies showed that as the task demands increase, the proportion of dwell time of the gaze directed toward task-relevant area of interest increases, narrowing attention. Vansteenkiste et al. (2013) proposed "the gaze constraints model" based on these observations and previous models of steering control in car driving (Donges, 1978; Salvucci & Gray, 2004). This model was proposed to apply to multiple forms of goal-directed locomotion and focus on "where" the gaze tends to be located in function of task demands. This model proposes that locomotor goal can be reached if two requirements are met: (i) "direct control for stability and vehicle control" and (ii) "anticipation for guidance and hazard perception" (Vansteenkiste et al., 2013). Direct control is characterized by gaze directed toward close regions whereas anticipation is characterized by gaze located in distant region. Thus, as the need for control increases (e.g., when riding a bike on low quality road or narrow path), performers appear to look closer to them, whereas when the task demand is low (e.g., the path width is wide) or when the need for anticipation is high (e.g., riding the bike at high speed), performers tend to look directly at the location to where they are heading. Also, one of the study showed that children were more prone than adults to direct their gaze toward irrelevant areas (Vansteenkiste et al., 2017). This difference can be due to children's lower experience with bicycling and/or more difficulties for them to distinguish what is relevant and what is not, suggesting that knowing "where to look" may require learning.

As illustrated by the visual system leading the wheel steering angle in car driving (Land & Lee, 1994; Land & Tatler, 2001), another issue resides in learning "when" to move the eyes in relation to action. Regarding this issue, walking on complex terrain was shown to require visual information to be available on at least a two steps lengths visibility window so that walking speed was not reduced and obstacles are avoided (Matthis & Fajen, 2014). It was also shown that the control of foot placement requires visual information in the last part of the stance phase of the leg that aims to a foot target location (Chapman & Hollands, 2006a; Matthis, Barton, & Fajen, 2017). These studies argue in favor of a proactive (feedforward) control of the foot placement: visual information about the target location is used before starting the step to the target so that walkers can adapt before the swinging phase. Although the swinging phase appears to hardly adapt to perturbation in the target location (Barton, Matthis, & Fajen, 2019), the analysis of gaze behaviors showed that as the task requirements increase (the size of the target decrease or the terrain is more difficult), online gaze control becomes determinant for accurate foot placement (Chapman & Hollands, 2006b; Matthis, Yates, & Hayhoe, 2018; Yamada et al., 2012). These findings showed that effective control of locomotion requires an appropriate timing of the eye movements in relation to body movements: actions that require high accuracy are better performed with foveal vision and online control (i.e., fixation toward the target during the movement), whereas actions requiring little accuracy (like walking on a flat terrain) can be achieved with proactive control and peripheral vision (Franchak & Adolph, 2010).

In sports context, this timing issue was mainly investigated in discrete tasks although sport skills often require performers to move their whole body while performing discrete tasks requiring accuracy. For example, a systematic review of football studies highlighted the lack of representative settings used to investigate visual activity (McGuckian, Cole, &

Pepping, 2018) although the ball manipulation with the feet and the navigation in a complex environment constrains importantly the eye movements. Representative settings require that performers use the visual system to control their unfolding action and to search for action opportunities (van Andel et al., 2019). The research paradigms inviting participants to walk on targets illustrate this dual demand on the visual system, but in these studies, the clues are all placed on the ground and in front of the walkers (e.g., Chapman & Hollands, 2006b) whereas they are more dispersed in sports context. One of the rare study examining this issue in a sporting continuous task compared the gaze behavior of expert and experienced skiers in alpine slalom skiing (Decroix et al., 2017). In this task, performers must control their actions to pass between poles forming gates while descending the slope. To optimize the trajectory, the authors hypothesized that experts would look more at second next and future poles, and would switch their gaze earlier to the next poles than less skilled participants (Decroix et al., 2017). The results showed that both groups rarely looked further than the second next pole, thus, they focused on the current turn to perform and the following one. The results showed as expected that experts looked more at the second next pole than the less skilled participants and experts switched their gaze earlier (in term of distance) to the next pole, suggesting that experts used more proactive gaze behavior to anticipate their trajectory. Also, results showed that less skilled participants looked more at the surface between gates, suggesting that they looked for information to better control their turns while experts did not (or peripheral visual information was sufficient for them) (Decroix et al., 2017). This study illustrates how this dual demand constrains gaze behaviors and that performers need to learn how to adjust their gaze in function of their skill level.

In other sporting contexts, action opportunities may arise from performers' surroundings. As the search may require large amplitudes of movement from the eye and the head and some movements may require the support of the foveal vision, performers need to appropriately coordinate the timing of periods of search to the timing of periods of control of the movement. Learning to be efficient in both search and control of actions can be critical for performance. In climbing for example, performers are often confronted to new performance contexts (climbing routes) which, in competition such as lead climbing, can present task difficulty approaching their maximum action capabilities. Thus, climbers must be able to search for opportunities of action to reach the top of the route, while controlling each of the performed limb action, which requires accuracy and strength (van Knobelsdorff, van Bergen, van der Kamp, Seifert, & Orth, 2020). Moreover, visual exploration must be sustained while maintaining postural stability, which may be difficult when holds used as support restrain body movements due to their size and/or shape (Dupuy & Ripoll, 1989). Thus, in such sporting context, performers must learn to appropriately embed the actions of their visual system in the flow of their body movements.

What Do we Know about Eye Movements During Skill Acquisition?

Interventions Aiming to Improve Pick-up of Information

Improving information pick-up was thought to be determinant to improve performance in sports. Thus, perceptual training interventions are developed to complement on-field training. However, the improvements made in perception skills with analytical vision training do not appear to transfer to task-specific sport skills, even when vision training is associated to sport-specific movements (Formenti et al., 2019). Similarly, some studies showed that imagery training program with elite football players yielded an increase of the visual exploratory activity during games, but the effects on performance were uncertain (Jordet, 2005; Pocock et al., 2019). The effects of imagery training program seemed however more promising to develop anticipation skills in cricket for instance (Smeeton, Hibbert, Stevenson, Cumming, & Williams, 2013).

Other forms of interventions originating from ecological psychology and the concept of education of attention (also referred to as attunement) were proposed. The first is the reduced usefulness training (Smeeton, Huys, et al., 2013). This kind of training consists of increasing the variability of some informational variables, so that learners attune to more reliable information for action with practice (Fajen & Devaney, 2006; Huet et al., 2011). For example, a study trained anticipation skills of goalkeepers on penalty kicks by having three players engaging in the run-up toward the ball but two would stop 1.2m away from the ball, so that the goalkeeper could only rely on information from this final phase of the run-up before the kick to anticipate its direction (Dicks, Pocock, et al., 2017). This intervention led to improvement in the performance of the goalkeepers in non-deceptive penalty kicks. The second form of intervention also aims to affect education of attention but this time not by varying some information variables but by manipulating its availability to improve the timing of the information pick-up. This intervention was applied to training basketball free throw using occlusion glasses so that visual information was only available in the 350ms period before the shoot (Oudejans, Koedijker, Bleijendaal, & Bakker, 2005). The results of this intervention suggest that restraining the availability of information can support performance improvement by lengthening the period during which it is relevant to pick-up information (i.e., by having the basket in sight during the shooting movement).

These studies showed that intervention can improve the perception-action coupling by playing on two possible levers linked to the concept of attunement (or education of attention): the informational variable on which performer rely and the timing of the pick-up of information. Although the first lever was extensively studied, notably using virtual environments (e.g., Fajen & Devaney, 2006; Huet et al., 2011), the second remains less investigated in skill acquisition in sport. This is notably due to a limitation of the presented studies as they assumed that practice yielded to attunement or better pickup of information by the visual system, but the changes in exploratory behaviors (i.e., actions performed to pick up information by the perceptual systems, notably in our interest, by the visual system) that led to the changes in terms of movement performance remain unknown.

Eye-Movements in Perceptual-motor Learning

As exposed in the introduction, an important range of the literature about eye movements in sport skill acquisition used cross-sectional study design, by comparing the eye movements of novices to skilled performers. The main findings that seem to generalize across such study design are that expert performers' attention was more narrowed than novices as they rely on fewer areas of interest in their environment and they perform fewer and longer fixations (Mann et al., 2007). However, these finding can be discussed when confronted to studies designed to examine within participants learning of a perceptual-motor task.

A seminal study described three learning stages during the practice of a perceptual-motor task (Sailer, Flanagan, & Johansson, 2005). Participants learnt to control a cursor on a screen by bimanually applying isometric force on a tool. With this cursor, they had to hit a series of targets. The results showed that gaze behavior could be categorized into three learning stages. During the initial stage, called the exploratory phase, the participants' performances were poor, and their gaze was dominantly following the cursor, occasionally moving toward the target. In the second phase, called skill acquisition, performance increased quickly, and the gaze was leading the cursor with larger gaze saccades. In the final stage, called skill refinement, improvement in term of performance were slower and the gaze was positioned on the target (Sailer et al., 2005). Thus, it appears that with practice, learners rely more on peripheral vision as they learn to control the cursor and that their gaze behavior became more goal directed. This gain in goal-directedness of the visual system was also observed when participants had to discover how to use the objects they had to manipulate (van Dijk & Bongers, 2014). In this study, the gain in goal-directedness was observed by a decrease in the number of fixations that was not associated to a hand movement toward the different objects at disposition (these fixations were considered as aiming to discover and investigate the objects), and an increase in the number of fixations followed by hand manipulation of the fixated object (van Dijk & Bongers, 2014).

It was already questioned whether these learning stages would apply to the learning of other eye-hand coordination (Land, 2005), which appears to be the case (e.g., Bosch, Hanna, Fercho, & Baugh, 2018). We broaden this question by asking whether these findings could apply to the acquisition of more complex skills and whether it is restrained to the coordination between the eyes and the hand movements or if it also applies to foot movements or whole-body movements including more central aspects of behavior (e.g., postural regulation). For example, in climbing, the location and size of handholds and footholds require accurate movements from hands and feet, but competitive context also temporally constrains the climbers' actions (e.g., in speed climbing, performers have to climb a route faster than a direct opponent and in lead climbing, the time is limited to reach the top of the route). One study showed that with practice, climbers decreased the number of fixations performed during trials (Button, Orth, Davids, & Seifert, 2018), but it remains to be determined whether this was due to a decrease in gaze activity to search the opportunities for action on the wall and with the holds and/or to changes in the visual control of the limbs actions.

Conclusion

We reviewed studies examining the gaze behaviors in relation to body movements to highlight potential directions that could be taken in the field of skill acquisition in sport. The study of gaze behaviors is promising to further the understanding of how actions are controlled in complex environments. However, the commonly reported fixations variables are insufficient to understand how performers manage to balance effectively the dual demand constraining their visual system. The timing of eye-movements in relation to events and actions may provide a relevant direction for further investigation about how performers learn to coordinate the search for upcoming movement possibilities and guide their current movements with peripheral and foveal vision in locomotion tasks. More studies examining within participants changes in gaze behavior following interventions are also needed to move beyond the comparisons of skilled and novice performers. This would also reveal whether the findings in perceptual-motor development and in learning of laboratory tasks apply to more naturalistic and more complex perceptual-motor skill learning.

Highlights

- The visual system is not limited to the eyes: it involves the coordination of different body structures, including other perceptual systems.
- Investigating performers' gaze behaviors in relation to body movements is relevant to better understand the visual control of action in complex tasks involving locomotion.
- In locomotion tasks, the visual system is constrained by a dual demand: guiding the current movements and searching for upcoming movement possibilities.
- Task demands importantly affect performers' gaze behaviors as they appear to balance the dual demand accordingly.
- Literature in skill acquisition needs more longitudinal study design to highlight within participants changes in the visual control of action.

Chapter 3: Variable Practice Conditions in Motor Learning

Introduction

In the motor learning literature, performing under different task conditions during practice would enhance learning according to different hypotheses. Increasing the range of experienced conditions and the frequency of changes were predicted to be beneficial for transfer of learning by the Schema Theory (Schmidt, 1975) and to facilitate retention, according to the Contextual Interference effect (J. B. Shea & Morgan, 1979). More recently, the Differential Learning hypothesis (Schöllhorn et al., 2009) and the Structural Learning hypothesis (Braun, Mehring, & Wolpert, 2010) have continued to predict beneficial effects of variations in task performance conditions. However, these hypotheses were associated to different designs of motor learning protocols that were adapted in function of research questions and findings from related studies. This development of the scientific literature led to an important diversity in the learning protocols that the current chapter aimed to sort out in order to reveal the current directions taken by scientists and practitioners.

More specifically, the aim of this chapter was to review experimental studies to examine how variability in practice is induced and for what purpose. Thus, the paper focused on the methods used to review (i) the investigated tasks, (ii) the nature of the variations between task conditions, (iii) the scheduling of the task conditions during practice, (iv) the tests performed to assess learning, and (v) the nature of the measured dependent variables.

Method

Search Strategy

Searches were completed on the 1st of October 2019 in the PubMed and Embase databases and followed PRISMA guidelines. First, duplicates were removed from the reference list. Then, titles and abstracts were screened. Finally, full texts were read to assess paper eligibility for the systematic review.

Inclusion Criteria

To be eligible for inclusion, studies were required: (i) to be an original full-length paper; (ii) to be peer-reviewed; (iii) be written in English; (iv) to be published later than January 2000; (v) to investigate healthy human individuals; (vi) to present a practice period on a motor or perceptual-motor task; (vii) to examine within- and/or post-practice effects, and (viii) to propose at least one group intervention with changes in task performance conditions during practice.

Keywords

Keywords were classified into four collections relating to: (i) learning; (ii) movement; (iii) variable practice condition; (iv) testing. Search results were obtained by linking the four collections of keywords with AND connector and keywords in the same collection were linked with OR connector (more details in **Supplementary Information**).

Results

Descriptive Statistics

A total of 1995 articles were retrieved through search in PubMed and Embase databases and 4 articles were identified through other sources. After screening and assessing the eligibility of the records, 92 articles were identified as suitable for inclusion (**Figure 3**). As some articles implemented several experiments, a total of 104 studies were examined for the qualitative synthesis. The number of articles per year range from 1 to 11 (M = 4.6). Articles were retrieved from 29 journals, and the most represented ones are Perceptual and Motor Skills (n = 19, including 14 before 2010), Journal of Motor Behavior (n = 10), Research Quarterly for Exercise and Sport (n = 9), Human Movement Science (n = 8), Journal of Neurophysiology (n = 6), Experimental Brain Research (n = 6), Plos One (n = 5) and Acta Psychologica (n = 4).

Participants

Of the 104 reviewed studies, 62 did not report the participants' prior experience with the task. For some studies, the unusual nature of some laboratory tasks suggests that participants had no prior experience performing it (e.g., performing pointing task under visuomotor rotation) but some studies used tasks where the lack of experience of the participants was not obvious (e.g., object throw to target, locomotor tasks). Participants were reported as having no prior experience in the task in 31 studies and 7 studies reported little experience (i.e., novices). Both skilled and novice participants were involved in 3 studies. Among these studies, 2 compared a group of skilled participants to a group of novices and 1 study mixed novices and skilled participants in the intervention groups. Only one study involved expert participants. This study was a case-study presenting an intervention on one high-level athlete, whose performances were compared to another expert.

Adults were largely the most studied population (n = 89, studies involving adults, often university students), followed by children (n = 7), adolescents (n = 2), and elderlies (n =

2). Additionally, 2 studies compared different age groups (Children vs. Adults and Children vs. Adolescents vs. Adults) and the participants' age could not be retrieved in 2 studies.

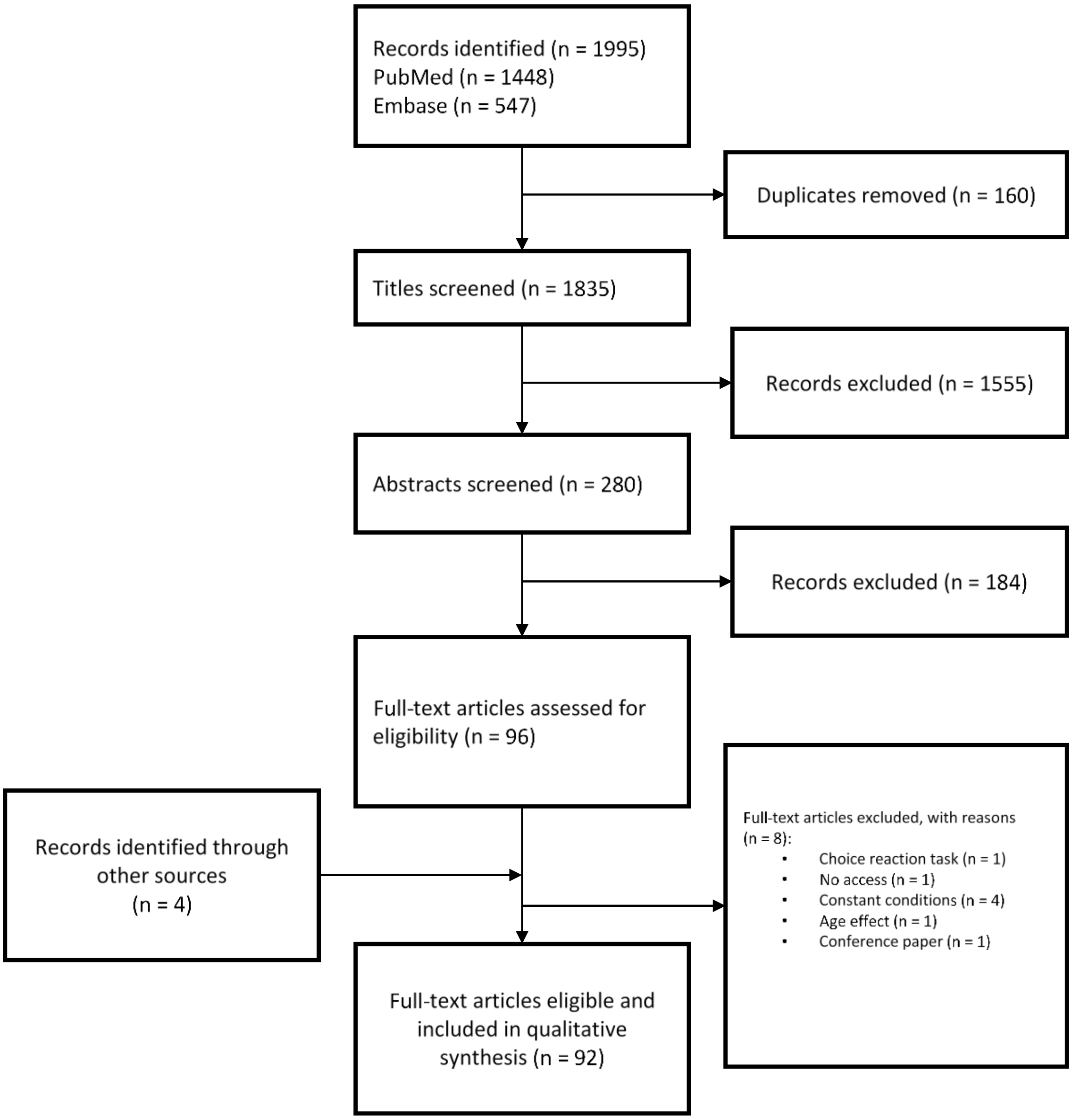

Figure 3. PRISMA flowchart

Variations

The taxonomy proposed by Ranganathan and Newell (2013) was initially used to classify the variations in the studies. This paper proposed to differentiate variability induced at the execution redundancy level from variability at the task goal level, namely variability in task conditions that encourages the performance of different movements achieving the same task outcomes from variability in task conditions inducing both new movement and task outcomes (Ranganathan & Newell, 2013). Variability at the task goal level was then divided into structured and unstructured variability, according to the number of task parameters that was varied (one or more, respectively).

After reading the articles, some categories were added (**Table 1**). First, multiple skills were trained simultaneously during practice in 26 studies (Ranganathan and Newell, 2013, mentioned this but did not cover it). Then, when structured variability was applied at the task goal level, some studies varied more specifically a sensorimotor perturbation (n = 14), a temporal constraint (n = 11), the task difficulty (n = 9), or a task-irrelevant parameter (n = 2). Structured variability at the task goal level was also applied in 23 other studies. Unstructured variability was applied at the task goal level in 8 studies and at the execution redundancy level in 6 studies. Different variations from different categories were used in some studies: multiple skills were combined with temporal constraints (n = 2), multiple skills were combined with variability at the task goal level (n = 1), variability at the task goal level was combined with variability at the execution redundancy level (n = 1) and variability at the task goal level was compared to variability at the execution redundancy level (n = 1).

Table 1. Definition of variation categories.

Variation Category	Definition	Example of Variations
Execution redundancy	Forcing exploration of different movement solution to reach the task goal	Obstacle height in basket shooting task
Task Goal Structured	Varying one task parameter	Distance from the target in aiming task
Task Goal Unstructured	Changing multiple task parameters simultaneously	Ball size, foot position, distance from target in throwing task
Multiple Skills	Training on different tasks within the same learning protocol	Multiple key-pressing sequence; Passing and shooting in football
Difficulty	Facilitating or hardening the conditions to reach the task-goal	Racquet width in interception task; initial speed in rollerball task
Sensorimotor Perturbation	Implementing perturbation in task condition requiring motor adaptation	Angle of VMR; acceleration of the treadmill in slipping task
Temporal Constraints	Modifying the timing between different actions in the task	Segment time in key-pressing task; Tempo in walking to metronome task
Irrelevant Task Parameter	Changing a task parameter irrelevant regarding movement performance and task goal	Ball color in putting task

Schedules of Variations

The schedules used to provide the task conditions during practice were categorized into five types (**Table 2**): (i) contextual Interference, (ii) variability, (iii) progressivity, (iv) self-regulated and (v) intervention. We also collected the number of trials performed before that the task conditions were changed.

Important heterogeneity was observed between studies about how the task variations were scheduled, and the number of trials given to participants to practice each task conditions, including when studies belonged to the same scheduling category. The contextual interference schedules were used in 48 studies, variability in 28 studies and 2 studies combined contextual interference and variability. Progressive change in difficulty was performed in 7 studies and self-regulated practice was used in 6 studies. Self-regulated practice and contextual interference were mixed in 2 studies and self-regulated practice was mixed with progressive change in difficulty in 2 studies. Finally, 9 studies were intervention studies referring to motor learning frameworks.

Table 2. Definition of schedules categories

Schedule Category	Definition	Example of Schedules
Contextual Interference	Different orders of task variations are compared.	Blocked, Serial, Random
Variability	One or multiple task parameters are varied	Variable, random, generally compared to constant practice or another variable group
Progressivity	Task parameters are changed gradually	Incremental, Gradual, Adaptive, generally compared to a constant practice condition
Self-regulated	Participants can choose when to change a task parameter	Self-controlled generally compared to yoked
Intervention	Intervention refers to a motor learning framework	Differential Learning, Nonlinear Pedagogy, generally compared to traditional / repetitive learning group

Task

Using the task classification proposed by Ranganathan, Tomlinson, Lokesh, Lin and Patel (2020) (**Table 3**), 30 studies were on sequence learning, 22 were on adaptation tasks, 21 were on applied tasks, 17 were on variability tasks, 8 were on tracking tasks and 6 were on coordination tasks. These tasks were mainly discrete tasks (including in applied tasks) generally performed in laboratory settings.

Table 3. Definition of task categories

Task Category	Process involved in learning of task	Typical dependent variable(s)	Example
Adaptation	Responding to perturbations of typically well-learned movements	Deviation from baseline behavior	Visuomotor rotation
Applied	Production of movement responses in "real-world" situations that may involve a combination of processes	Task-dependent	Shooting task in soccer
Coordination	Production of spatiotemporal pattern involving more than a single degree of freedom (limbs, joints, muscles)	Coordination measures that capture relative motion between the degrees of freedom, dimensionality reduction techniques	Bimanual coordination
Sequence	Production of a sequence of several movement responses	Speed, errors, reaction time	Key-pressing
Tracking	Production of a desired spatiotemporal pattern that is « time varying »	Deviation between the target pattern and the actual	Tracking of a moving target on a screen
Variability	Production of a « steady-state » task performance level over time or trials	Variability across time or trials	Throwing a ball to a target

Note: this table was originally published in Ranganathan et al. (2020).

Practice Effect

A baseline measure prior to practice was performed in only 47 studies (e.g., pretest). Dependent variables were collected during practice in 70 studies. The remaining 34 studies evaluated practice effects only with test performed after the practice period. When dependent variables were collected during practice, they were in general presented in 1 or more blocks of trials (n = 60 studies). Post-tests were performed immediately after practice in 43 studies. Transfer tests, including probe or catch trials performed during practice, were used in 52 studies. Delayed tests performed after the end of the practice period were used in 74 studies. These delayed tests could be retention tests and/or transfer tests.

Most of the studies reported measures of task performance (n = 94). Behavioral measures were used in 39 studies. Individual values were presented in only 8 studies, and intra-group variability was assessed with standard deviation and standard error of the mean in general (n = 85).

The studies are summarized in **Table 4**.

Table 4. Characteristics of the included studies (N = 104)

Authors / Year	N / Skill / Age	Task(s)	Task Category	Source(s) of Variation	Variation Category	Schedule Category	Frequency of Variations
Andrieux, Boutin, & Thon / 2016	12 / No / Adults	Virtual Target Interception	Variability	Racquet Width	Difficulty	Self	Each trial
Andrieux, Danna, & Thon / 2012	18 / No / Adults	Virtual Target Interception	Variability	Racquet Width	Difficulty	Self	Each trial
Bertollo, Berchicci, Carraro, Comani, & Robazza / 2010	20 / No / Adults	Rhythmic Footstep Sequences on a video game	Sequence	Rhythmic Footstep Sequences (x3)	Multiple Skills	CI	Each trial / Each 2 sessions
Bonney, Jelsma, Ferguson, & Smits-Engelsman / 2017	55.5 / No / Children	Play videogame (Exergames)	Applied	Exergame played (x10)	Multiple Skills	Var	Unknown / None
Bortoli, Spagolla, & Robazza / 2001	12 / ? / Children	Sandbag precision throwing / Quintuple jumping / Hurdle running	Applied	Task (x3) and/or Parameter (x3)	Multiple Skills x Task-Goal	CI x Var	9 trials /3 trials / 3 trials / 3 trials
Braun, Aertsen, Wolpert, & Mehring / 2009 Exp. 1	19 / ? / Adults	Pointing task with visuomotor transformation	Adaptation	Rotation angle / Combined rotation, shearing and scaling applied to cursor location / None	Sensorimotor Perturbation	Var	8 trials / 8 trials / None
Braun et al. / 2009 Exp. 2	4 / ? / Adults	Pointing task with visuomotor transformation	Adaptation	Rotation angle / Shearing transformation	Sensorimotor Perturbation	Var	Each trial
Braun et al. / 2009 Exp. 3	6 / ? / Adults	Pointing task with visuomotor transformation	Adaptation	Horizontal rotation angle / Vertical rotation angle	Sensorimotor Perturbation	Var	Each trial
Breslin, Hodges, Steenson, & Williams / 2012	10 / No / Adults	Basketball Free throw	Applied	Distance from the basket (5 distances)	Task-Goal Structured	Var	None / 20 trials
Caramiaux, Bevilacqua, Wanderley, & Palmer / 2018	12 / No / Adults	Produce musical sequence on a piano keyboard	Sequence	Tempo variability (x2)	Temporal constraints	CI	6 trials / 6 trials / 6 trials / 6 trials

Authors / Year	N / Skill / Age	Task(s)	Task Category	Source(s) of Variation	Variation Category	Schedule Category	Frequency of Variations
Cardis, Casadio, & Ranganathan / 2018	10 / ? / Adults	Virtual shuffleboard task	Coordination	Hands' velocity	Sensorimotor Perturbation	Var	None / Each trial
Choi, Qi, Gordon, & Schweighofer / 2008	12 / ? / Adults	Pointing task with visuomotor transformation	Adaptation	Angle of visuomotor transformation (x4) / Time limit for two groups	Sensorimotor Perturbation	Prog	Task in each trial / Difficulty on each trial for adaptive difficulty groups
Cohen, Bloomberg, & Mulavara / 2005	40 / ? / Adults	Locomotor task with obstacles	Adaptation	visual distortion lens (3 different in variable practice)	Sensorimotor Perturbation	Var	None / None / None / 10 minutes
Douvis / 2005	10 / No / Children and Adults	Tennis forehand drive	Applied	Targets (x4 or x5)	Task-Goal Structured	Var	No / No / 25 trials / 20 trials
Dubrowski, Proteau, & Carnahan / 2004	8 / ? / Adults	Grasp and lift an object	Adaptation	Object mass and color cue (x3)	Sensorimotor Perturbation	CI	30 trials / Each trial / Each trial
Forner-Cordero, Quadrado, Tsagbey, & Smits-Engelsman / 2018	20 / ? / Adults	Virtual interception task	Adaptation	Stiffness of elastic bands (x3)	Sensorimotor Perturbation	Var	None / None / Each trial
Fromer, Sturmer, & Sommer / 2016a	120 / ? / Adults	Virtual dart throwing	Variability	Target Position (x3)	Task-Goal Structured	CI	5 trials / Each trial
Fromer, Sturmer, & Sommer / 2016b	96 / ? / Adults	Virtual dart throwing	Variability	Target Position (x3)	Task-Goal Structured	CI	5 trials / Each trial
Gill, Pu, Woo, & Kim / 2018	30 / No / Adults	Walking to metronome pace	Adaptation	Metronome pace (x3)	Temporal constraints	CI	10 trials / Each trial
Giuffrida, Shea, & Fairbrother / 2002	18 / No / Adults	Key-press timing task	Sequence	Movement time (x3)	Temporal constraints	CI	No / 3 or 9 blocks / Each trial
Granda Vera & Montilla / 2003	35.5 / ? / Children	Throwing an object to a target	Variability	Type of the ball / Distance from the target / Position of the target	Task-Goal Unstructured	CI	Each session / Each trial
Hedges, Edwards, Luttin, & Bowcock / 2011	10 / Experts and Novices / Adults	Disc throwing to target	Variability	Throwing hand / Throwing technique (x2)	Execution Redundancy	Self	Each trial / Each trial /Each trial
Heitman, Pugh, Kovaleski, Norell, & Vicory / 2005	10 / ? / Adults	Pursuit task on a photoelectric instrument	Tracking	Speed (x3)	Difficulty	Var	Each trial / None / None

Authors / Year	N / Skill / Age	Task(s)	Task Category	Source(s) of Variation	Variation Category	Schedule Category	Frequency of Variations
Hinkel-Lipsker & Hahn / 2017	16 / ? / Adults	Walking on a split belt treadmill	Adaptation	Speed of one treadmill	Difficulty	CI	Each stride / Each stride / Each 20 strides
Hinkel-Lipsker & Hahn / 2018	16 / ? / Adults	Walking on a split belt treadmill	Adaptation	Speed of one treadmill	Difficulty	CI	Each trial / Each trial / Each 20 strides
Horbacewicz / 2018	26 / No / Adults	Hand force production task	Variability	Force to produce (x2)	Task-Goal Structured	CI	30 trials / Each trial
Hossner, Käch, & Enz / 2016 Exp. 1	10 / Skilled / Adolescents	Football shooting task	Applied	Exercises (3-4 per session) / 13 sources of variations	Task-Goal Unstructured	Inter	8-10 trials / 1-3 trials / 1-3 trials
Hossner et al. / 2016 Exp. 2	12 / Novices / Adults	Shot put task	Applied	7 sources of variations	Task-Goal Unstructured	Inter	4 to 12 trials / Each trial / Each trial
Hussain & Morton / 2014	16 / ? / Adults	Walking on a treadmill with a perturbed leg	Adaptation	Weight of the resistance on the perturbed leg	Sensorimotor Perturbation	Prog	Each minute / None
Immink & Wright / 2001 Exp. 1	15 / ? / Adults	Key-press timing task	Sequence	Timing task (x2)	Multiple Skills	CI	30 trials / Each trials
Immink & Wright / 2001 Exp. 2	15 / ? / Adults	Key-press timing task	Sequence	Timing task (x4)	Multiple Skills	CI	32 trials / Each trial
James / 2014	16.5 / ? / Adults	Postural task	Variability	Stance / Weight position / Body movements	Task-Goal Unstructured	Inter	Each trial / None
James & Conatser / 2014	13.5 / ? / Adults	Rhythmic unimanual arm rotation task	Coordination	Arm orientation (x3) / Training movement (x7)	Task-Goal Unstructured	Inter	None / Each trial
Jarus & Gutman / 2001	16 / ? / Children	Throw a beanbag to a target	Variability	Weight in simple task condition / size, weight and color in complex task condition	Task-Goal Structured	CI	Each trial / 10 trials / 5 trials + Each trial / Each trial + 5 trials
K. Jones & Croot / 2016	9 / ? / Adults	Read tongue twister	Adaptation	Tongue twister (x20)	Multiple Skills	CI	Each trial / 16 trials/ 8 trials+ Each trial / Each trial + 8 trials
L. L. Jones & French / 2007	17 / ? / Adolescents	Volleyball skills (x3)	Applied	the volleyball skill	Multiple Skills	CI	Each trials / 90 trials (3 sessions) / 10 trials
Kantak, Sullivan, Fisher, Knowlton, & Winstein / 2011	15 / ? / Adults	Move a lever to replicate a target trajectory	Tracking	target of peak amplitude (x4)	Task-Goal Structured	Var	None / About each 4 trials

Authors / Year	N / Skill / Age	Task(s)	Task Category	Source(s) of Variation	Variation Category	Schedule Category	Frequency of Variations
Karlinsky & Hodges / 2018	16 pairs / ? / Adults	Key-press timing task	Sequence	Timing task (x3)	Multiple Skills	Self-CI	24 trials / Each trial / Each trial
Keetch & Lee / 2007	12 / ? / Adults	Sequence of aim and click movements	Sequence	Arrangement of targets (x4)	Multiple Skills	Self-CI	32 trials / Each trial / Each trial / Each trial
Kim, Chen, Verwey, & Wright / 2018	12 / No / Adults	Discrete sequence production task	Sequence	Sequence (x3)	Multiple Skills	CI	99 trials / Each trial / None
Kim, Rhee, & Wright / 2016 Exp. 1	15 / No / Adults	Discrete sequence production task	Sequence	Sequence (x3)	Multiple Skills	CI	9 trials / Each trial / None
Kim et al. / 2016 Exp. 2	17 / No / Adults	Discrete sequence production task	Sequence	Sequence (x3)	Multiple Skills	CI	9 trials / Each trial / None
King & Newell / 2014	10 / ? / Adults	Isometric force production task according to target pattern	Tracking	Force-time wave form	Task-Goal Structured	Var	None / Each trial
Klassen, Tong, & Flanagan / 2005	8 / ? / Adults	Pointing task with visuomotor transformation	Adaptation	Rotation angle (kinematic) or viscosity of the velocity-dependent rotary force-field (dynamic)	Sensorimotor Perturbation	Prog	Each trial / None
Kruisselbrink & Van Gyn / 2011	10 / ? / Adults	Key-press timing task	Sequence	Task (x3)	Multiple Skills	CI	18 trials / Each trial
Lai, Shea, Wulf, & Wright / 2000 Exp. 1	10 / No / Adults	Key-press timing task	Sequence	Goal MT (x3)	Temporal constraints	Var	None / Each trial
Lai et al. / 2000 Exp. 2	10 / No / Adults	Key-press timing task	Sequence	Goal MT (x3)	Temporal constraints	Var	None / None + Each trial / Each trial + None / Each trial
Lee, Chow, Komar, Tan, & Button / 2014	10 / Novices / Adults	Learn the forehand stroke in tennis	Applied	Exercises / Change in equipment or instructions	Task-Goal Unstructured	Inter	Unknown
Leving, Vegter, de Groot, & van der Woude / 2016	11.5 / No / Adults	Wheelchair tasks	Applied	wheelchair tasks (x6)	Multiple Skills	Inter	None / Unknown

Authors / Year	N / Skill / Age	Task(s)	Task Category	Source(s) of Variation	Variation Category	Schedule Category	Frequency of Variations
Lewthwaite, Chiviacowsky, Drews, & Wulf / 2015 Exp. 1	12 / No / Adults	Golf putting task	Applied	Ball color	Irrelevant Parameter	Self	10 trials / 10 trials
Lin, Sullivan, Wu, Kantak, & Winstein / 2007	10 / ? / Elderlies	Replicate a pattern with a lever	Tracking	The targeted trajectory (x3)	Task-Goal Structured	CI	45 trials / Each trial
Lin, Winstein, Fisher, & Wu / 2010 Exp. 1	10 / ? / Adults	Replicate a pattern with a lever	Tracking	The targeted trajectory (x3)	Task-Goal Structured	CI	48 trials / Each trial
Lin et al. / 2010 Exp. 2	10 / ? / Elderlies	Replicate a pattern with a lever	Tracking	The targeted trajectory (x3)	Task-Goal Structured	Var	Each trial
Y.-T. Liu, Luo, Mayer-Kress, & Newell / 2012 Exp. 1	10 / ? / Adults	Roller ball task	Coordination	Initial speed of the roller ball	Difficulty	Self-Prog	Each trial / 10 trials
Liu, Luo, Mayer-Kress and Newell 2012 Exp 2	7 / ? / Adults	Roller ball task	Coordination	Initial speed of the roller ball	Difficulty	Self-Prog	Each trial / 10 trials
X. Liu, Bhatt, & Pai / 2016	9 / ? / Adults	Walking on a treadmill with occasional slips	Adaptation	Acceleration of the treadmill	Sensorimotor Perturbation	Prog	None / None / Each block of 6 slips
Maslovat, Chus, Lee, & Franks / 2004	10 / ? / ?	Bimanual coordination	Coordination	RP between hands (x2)	Multiple Skills	CI	100 trials / Each trial / None
Mattar & Ostry / 2007	8 / ? / Adults	Reaching movements to a target with clockwise force field	Adaptation	Number and location of targets	Task-Goal Structured	Var	Each trial / None
Meira & Tani / 2001	16 / No / Adults	Dart throwing task	Applied	Distance from target (x2) / Grip on the dart (x2)	Task-Goal x Redundancy	CI	20 trials / Each trial
Meira, Fairbrother, & Perez / 2015	10 / No / Adults	Key-press timing task	Sequence	Movement time (x3)	Temporal constraints	CI	36 trials / Each trial
Memmert / 2006	16 / Novices / Adults	Basketball Shooting	Applied	Shooter position (x4)	Task-Goal Structured	Var	None / Each trial
North et al. / 2019	10 / Novices / Adults	Backhand shot in table tennis to a target	Applied	Movement instructions (x3)	Execution Redundancy	CI	None / 50 trials / Each trial

Authors / Year	N / Skill / Age	Task(s)	Task Category	Source(s) of Variation	Variation Category	Schedule Category	Frequency of Variations
Pabel, Pabel, Schmickler, Schulz, & Wiegand / 2017	36.5 / No / Adults	Prepare gold partial crowns	Applied	Conditions (x20)	Task-Goal Unstructured	Inter	None / 30 min
Pacheco & Newell / 2018	8 / ? / Adults	Throw a plastic golf ball to a target	Variability	Distance (x5) or Angle (x5) to the target	Task-Goal Structured	Var	None / Each trial / Each trial
Patterson, Carter, & Hansen / 2013	12 / ? / Adults	Key-press timing task	Sequence	Key sequence (x5) and movement time (3 variations)	Multiple Skills	CI	30 trials / Each trial
Pauwels, Swinnen, & Beets / 2014	20 / ? / Adults	Visuomotor bimanual tracking task	Coordination	Freq. ratio (x3) and Coordination direction (x2)	Multiple Skills	CI	72 trials for coordination direction - 144 trials for freq. ratio / Each trial
Perez, Meira, & Tani / 2005	28.5 / ? / Children	Lever positioning	Variability	the position to reach (x3)	Task-Goal Structured	CI	20 trials / Each trial
Porter & Magill / 2010 Exp. 1	20 / Novices / Adults	Golf putting task	Applied	Distance (x3)	Task-Goal Structured	CI	27 trials / Each trial / 9 trials + Each trial + Each trial
Porter & Magill / 2010 Exp. 2	32 / Novices / Adults	Pass of a basketball	Applied	Passing technique (x3)	Execution Redundancy	CI	27 trials / Each trial / 9 trials + Each trial + Each trial
Raisbeck, Regal, Diekfuss, Rhea, & Ward / 2015	12 / ? / Adults	Key-press timing task	Sequence	Timing sequence (x2)	Temporal constraints	CI	32 trials / Each trial
Ranganathan & Newell / 2010a	6 / ? / Adults	Virtual interception task	Variability	Obstacle position (range of 1cm or 2cm)	Execution Redundancy	Var	None / Each trial / Each trial
Ranganathan & Newell / 2010b	8 / ? / Adults	Virtual interception task	Variability	Position of the target or Position of an intermediate target	Task-Goal or Execution Redundancy	Var	None / Each trial / None / Each trial
Rivard et al. / 2015	12 / No / Adults	Laparoscopic surgery	Applied	Exercises of laparoscopic surgery	Multiple Skills	CI	4 to 12 trials / Each trial / None
Russell & Newell / 2007	24 / No / Adults	Rapid key-pressing sequence	Sequence	Key sequence (x3)	Multiple Skills	CI	18 trials / Each trial
Sawers & Hahn / 2013	8 / ? / Adults	Walking on a split belt treadmill	Adaptation	Speed of the treadmill on the dominant leg	Difficulty	Prog	20 strides / None

Authors / Year	N / Skill / Age	Task(s)	Task Category	Source(s) of Variation	Variation Category	Schedule Category	Frequency of Variations
Sawers, Kelly, Kartin, & Hahn / 2013	8 / No / Adults	Walking on a split belt treadmill	Adaptation	Speed of the treadmill on the dominant leg	Difficulty	Prog	20 strides / None
Sekiya / 2006	8 / ? / Adults	Tracking a target cursor moving in waveform pattern	Tracking	Shape of segments in the waveform pattern (3 segments)	Task-Goal Structured	CI	For segment 2: 30 trials / Each trial; for segment 1 and 3: each trial
C. H. Shea, Lai, Wright, Immink, & Black / 2001 Exp. 1	10 / No / Adults	Key-press timing task	Sequence	Goal MT (x3)	Temporal constraints	CI	None / 36 trials / Each trial / Each trial
C. H. Shea et al. / 2001	12 / No / Adults	Key-press timing task	Sequence	Goal MT (x3)	Temporal constraints	CI	36 trials / Each trial
Simon & Bjork / 2001	24 / ? / Adults	Key-press timing task	Sequence	Sequence and Goal MT jointly (x3)	Multiple Skills	CI	30 trials / Each trial
Simon / 2007	19.5 / ? / Adults	Key-press timing task	Sequence	Sequence and Goal MT jointly (x2)	Multiple Skills	CI	30 trials / Each trial
Simon & Bjork / 2002	24 / ? / Adults	Key-press timing task	Sequence	Sequence and Goal MT jointly (x3)	Multiple Skills	CI	30 trials / Each trial
Simon, Lee, & Cullen / 2008	12 / ? / Adults	Key-press timing task	Sequence	Sequence and Goal MT jointly (x3)	Multiple Skills	CI	24 trials / Each trial / Each trial with performance criterion reach /2 trials with performance criterion reach
Taheri, Fazeli, & Poureghbali / 2017	6 / Novices and Skilled / Adults	Basketball free throws	Applied	Height of an obstacle (x5)	Execution Redundancy	Var	None / Each trial
Takahashi et al. / 2003	27.5 / ? / Children, Adolescents and Adults	Displace a robot arm toward a target as quickly as possible	Adaptation	Noise in a Force field	Sensorimotor Perturbation	Var	None + Each trial / Each trial + None
Tanaka, Honda, Hanakawa, & Cohen / 2010 Exp. 1	15 / ? / Adults	Sequential visuomotor task	Sequence	Sequence of target (x3)	Multiple Skills	CI	24 trials / Each trial
Tanaka et al. / 2010 Exp. 2	13 / ? / Adults	Sequential visuomotor task	Sequence	Sequence of target (x3)	Multiple Skills	CI	24 trials / Each trial
Tuitert et al. / 2017	11 / ? / Adults	Target-pointing task with obstacle	Adaptation	Height of an obstacle (x10)	Execution Redundancy	Var	30 trials / None

Authors / Year	N / Skill / Age	Task(s)	Task Category	Source(s) of Variation	Variation Category	Schedule Category	Frequency of Variations
Turnham, Braun, & Wolpert / 2012	7 / ? / ?	Pointing task with visuomotor transformation	Adaptation	Rotation angle	Sensorimotor Perturbation	Prog	Each trial / Each trial / Each trial / None
Ullén & Bengtsson / 2003 Exp. 1	6 / ? / Adults	Rhythmic sequences of key-pressing	Sequence	Sequence and/or timing (x3)	Multiple Skills x Temporal Constraints	CI	Until reaching performance criterion / Until reaching performance criterion
Ullén & Bengtsson / 2003 Exp. 2	2 / ? / Adults	Rhythmic sequences of key-pressing	Sequence	Key sequence or timing between keypresses or both	Multiple Skills x Temporal Constraints	CI	Each trial and each block
Vera, Alvarez, & Medina / 2008	22 / Novices and Skilled / Children	Shooting and dribbling tasks	Applied	Football skills (x2)	Multiple Skills	CI x Var	7 sessions / Mix within session / Alternation between one task and mix
Wagner & Muller / 2008	1 / Expert / Adult	Ball Throwing tasks	Applied	Multiples task parameters	Task-Goal Unstructured	Inter	Each trial
Wang, Bhatt, Yang, & Pai / 2011	20 / ? / Adults	Sit-to-stand-slip task	Adaptation	Slips or nonslip	Sensorimotor Perturbation	Inter	1, 3, or 5 trials / None
Werner & Bock / 2007	10 / ? / Adults	Pointing task with visuomotor rotation	Adaptation	Location of target (x8)	Task-Goal Structured	Var	Each trial / Each trial in random
Whitacre & Shea / 2002	10 / No / Adults	Isometric force production task according to target waveform pattern	Tracking	Absolute timing (x6)	Task-Goal Structured	Var	None / Each trial
Wilde, Magnuson, & Shea / 2005	9 / No / Adults	Key-stroke sequence production	Sequence	Sequence (x3)	Multiple Skills	CI	240 trials / Each trial
Willey & Liu / 2018 Exp. 1	10 / ? / Adults	Bean bags throws to target	Variability	Distance from the aim (x2)	Task-Goal Structured	Var	None / Each trials
Willey & Liu / 2018 Exp. 2	10 / ? / Adults	Bean bags throws to target	Variability	Distance from the aim (x2)	Task-Goal Structured	Var	None / Each trials
Wright & Shea / 2001	12 / No / Adults	Key-press relative timing task	Sequence	Goal MT (x3)	Temporal constraints	CI	36 trials / Each trial
Wu et al. / 2011	20.5 / ? / Adults	Lever positioning in limited time	Variability	Target position (x4)	Task-Goal Structured	CI	48 trials / Each trial

Authors / Year	N / Skill / Age	Task(s)	Task Category	Source(s) of Variation	Variation Category	Schedule Category	Frequency of Variations
Wu & Magill / 2011	15 / No / Adults	Key-press relative timing task	Sequence	Goal MT (x3)	Temporal constraints	Self	Each trial
Wulf, Lewthwaite, Cardozo, & Chiviacowsky / 2018	15 / ? / Adults	Throw balls to a target	Variability	Throwing arm	Irrelevant Parameter	Self	5 trials
Yao, DeSola, & Bi / 2009	12 / No / Adults	Wheelchair locomotion at a target speed	Applied	Target speed	Task-Goal Structured	Var	None / None / 5 min

Note: This table presents the 104 experiments from the reviewed articles, each line corresponding to one experiment.
N is the number of participants per group, *No* refers to no experience in the task, *?* means that participants skill level was not reported
MT is the movement time.
CI stands for contextual interference, *Var* for variability, *Self* for self-regulated, *Prog* for progressivity and *Inter* for intervention.

Discussion

This paper aimed to review the range of methods used to infuse variability in the practice conditions and to review the purpose of such intervention. Our results confirmed the previously observed fragmentation in task paradigms used in motor learning studies (Ranganathan et al., 2020) and showed that the methods used to provide variability are also highly fragmented. In what follows, the source of variations in relation to the performed tasks is discussed (i.e., what to vary?). Then, the schedules of the task conditions are presented in relation to the main hypotheses they refer to (i.e., how are organized the task condition variations in practice?). Finally, the performed tests and the nature of the dependent variables are examined in the light of the main hypotheses of the studies (i.e., what are the expected practice effects?).

What to vary?

The results showed that changing the task itself from trial to trial and thus, training multiple skills during practice appears to be the most studied variations. However, the links between skills differ importantly across studies. First and most commonly, the skills can be movements performed by the same effector (e.g., the hand and fingers when practicing different key-pressing sequences on a keyboard). In this situation, the movement (or the sequence of actions) is generally confounded with the task goal (e.g., practicing two bimanual coordination patterns, Maslovat, Lam, Brunke, Chua, & Franks, 2009). Second, the skills can also belong to a single activity. The skills can involve very different characteristics in movement performance (e.g., speed vs. accuracy in Vera et al., 2008) but share some common aspects notably regarding object or tool manipulation (e.g., football manipulation in Vera et al., 2008). In this situation, the studies protocols appeared closer to real physical education lessons (Bortoli et al., 2001) or training sessions using applied skills such as sports skills (e.g., volley ball skills in L. L. Jones & French, 2007; football skills in Vera et al., 2008), surgery skills (Rivard et al., 2015) or wheelchair manipulation skills (Leving et al., 2016). Third, the practiced skills can also serve a more general purpose, such as developing everyday motor skills. For example, one study proposed an intervention involving the practice of different exergames in the aim of improving different motor skills (e.g., balance, agility, and coordination skills) (Bonney et al., 2017). Here, the different tasks share very few components.

When the task goal is not the movement itself, it is generally possible to achieve the task goal with different movement solutions. The variations in the task conditions were used in some studies to help learners demonstrate such functional equivalence (Komar, Chow, Chollet, & Seifert, 2015). That is, variations were designed to encourage the exploration of different movement solutions, which was referred to as variability at the execution redundancy level. In some studies, this was done by directly making the participants train different movement forms to achieve the task. For example in disc throwing towards a target, backhand and forehand technique are trained simultaneously (Hedges et al., 2011). Similarly in table tennis, backhand is varied by instructing on which side the follow through of the shot must be directed (North et al., 2019). Otherwise, task constraints can be varied to invite performers to discover the solution manifolds without imposing any movement solution. In general, this is achieved by constraining the range of movement solutions and changing this range during practice. For example, an intermediate target was added and manipulated in a virtual interception task to force learners to explore different trajectories to reach the target (Ranganathan & Newell, 2010a). In another study, the range of possible trajectories that the basketball could take in a free throw task was constrained by changing the height of an obstacle between the shooter and the basket (Taheri et al., 2017).

Variability was applied also at the task goal level. On one hand, this variability could be performed by manipulating multiple task parameters simultaneously. This was generally used to force learners' exploration, but in a much wider range than variations at the execution redundancy level as this time, the variations in the task goal force the exploration of new movement solutions in each task conditions and raise different task outcomes. For example, when learning a football shooting task, variants were applied to the supporting leg, the kicking foot, the trunk position, the approach, the kicking movement and/or the ball characteristics (Hossner et al., 2016). As multiple task parameters are changed simultaneously, this was performed mainly on applied skills involving complex multiarticular movements (e.g., the football shooting task and the shot put task in Hossner et al., 2016). However, one study used a more simple laboratory task (i.e., a unimanual arm rotation task) but the aim of this study was precisely to examine whether a high variability training was also beneficial to learning in simpler tasks (James & Conatser, 2014). The results in the retention test of this study confirmed that varying multiple task parameters benefit learning in comparison to a constant practice conditions even in a simple movement task (James & Conatser, 2014).

On the other hand, variations could be applied to the task goal by manipulating a single task parameter. In this context, learners' exploration is directed toward the varied parameter. For example, in aiming tasks, which are often used, it generally consists of varying the distance or the angle from the target (e.g., Pacheco & Newell, 2018). The results also revealed that some studies could be grouped as they manipulated similar task parameters that affected a temporal constraint on task completion, the task difficulty, or an irrelevant task parameter. The manipulation of temporal constraints requires the learner to adapt the temporal structure of their movements to the different conditions. The tasks demanded from learners to perform a sequence of actions, but the required timing between the actions was varied across trials. For example, the tasks could consist of perform a sequence on a piano at different tempos (Caramiaux et al., 2018) or to walk at the rhythm imposed by a metronome (Gill et al., 2018). Then, the manipulation of task difficulty was performed by changing the initial task constraints so that the margins for errors in task completion would be reduced or increased across task conditions. For example, two studies manipulated the racquet width in a virtual interception task (Andrieux et al., 2016, 2012), and two studies manipulated the initial speed in a rollerball task (Y.-T. Liu et al., 2012). Finally, two studies manipulated an irrelevant task parameter during practice, namely a parameter that neither affect the skill to learn nor the movement performance. One study changed the ball color in a golf putting task (Lewthwaite et al., 2015), and the second study allowed learners to practice with their dominant arm on some trials a throwing task although participants were aware that the skill to learn was throwing with their non-dominant arm (Wulf et al., 2018). These two studies showed that varying these parameters benefited to learning when the variations were controlled by learners, as it created a more autonomy-supportive learning environment (the purpose of such intervention is discussed in the following section).

Finally, some studies manipulated sensorimotor perturbations during practice. These were applied to already well-learned task skills, such as walking tasks on treadmill or pointing/reaching movement tasks. These perturbations could be sudden (e.g., experiencing an acceleration of a treadmill while walking to simulate a slip, X. Liu et al., 2016), or it could be continuous (e.g., walking with a weight on a leg (Hussain & Morton, 2014). The perturbations could also be applied more specifically to the visual feedback, notably performing a pointing task while experiencing a visuomotor rotation (Braun et al., 2009; Choi et al., 2008; Klassen et al., 2005; Turnham et al., 2012) or performing locomotor task wearing distortion glasses (Cohen et al., 2005).

In summary, the reviewed protocols have in common to provide conditions that force learners to experience different performance contexts with the purpose of disturbing the perceptual-motor system. At the exception of the study manipulating the ball color in the putting task (Lewthwaite et al., 2015) or the studies disturbing the visual feedback, the variations invited learners to perform different movement forms during practice. However, the differences between the movement forms that are expected vary importantly across protocols, ranging from performing small variations of the same movement to performing different movement skills involving different effectors. In the following section, the organizations of the task conditions variations are presented in relation to the purposes these organizations are designed for.

How are Task Condition Variations Organized in Practice?

The studies often used a between-group design comparing different schedules of task conditions. Notably, these schedules were designed with the purpose to provide different levels of contextual interference according to the group. The level of contextual interference corresponds to the amount of variations in task conditions experienced during practice. Based on Battig (1978) conceptualization of memory, Shea and Morgan (1979) proposed that higher level of contextual interference would facilitate learning (more details on contextual interference in the following section). In this context, the number of task conditions and the number of trials per condition are controlled so that only the schedule differs between groups. The highest contextual interference is usually provided with random practice, that is, the order of the conditions is pseudo-randomly assigned so that participants are confronted to a different condition on trial n+1 than on trial n. The lowest contextual interference is provided with blocked practice, where all trials in one condition are performed before practicing in a new condition. The results showed that the number of trials and time before changing the task conditions is highly variable across studies using blocked practice. It ranged from a few trials (e.g., 10 trials in Gill et al., 2018) to several sessions (e.g., 2 sessions in Bertollo et al., 2010) before practicing a new task condition. Finally, serial practice is proposed as an intermediate level of contextual interference by changing the condition in each trial, but in an order that is repeated throughout practice, which, contrarily to random schedules, enables learners to predict the task condition for each trial. Some studies also changed the level of contextual interference during practice, hypothesizing that increasing the level of contextual interference during practice would facilitate learning, as for example, scheduling half of the blocks of trials in a blocked order and the other half in a random order (e.g., K. Jones & Croot, 2016). The same practice schedules were also compared in some studies referring to contextual interference, but in the purpose of investigating the role of different brain areas to which transcranial magnetic stimulations were performed (Kantak et al., 2011; Lin et al., 2010; Tanaka et al., 2010).

Task performance conditions can also be changed in each trial systematically. Such variable practice condition can be compared to a constant (or repetitive) practice schedule. In this case, the aim is to examine the effect of varying conditions of practice and to assess whether it is beneficial for learning. Such protocols often refer to the Schema Theory and the Variability of Practice hypothesis (Schmidt, 1975). This hypothesis proposed that experiencing different movements controlled with the same generalized motor program in practice would enable to test different parameters in the generalized motor program and enhance the optimization of a recall and a recognition schema (which would facilitate latter adaptation of this movement). However, this hypothesis was initially formulated to investigate discrete movement tasks where the movement production was the task goal. More recently, applying variable practice to supra-coordinative tasks (i.e., goal-directed actions) has been hypothesized to increase movement variability, which would facilitate the search for movement solutions by the motor system in comparison to constant practice (e.g., Cardis et al., 2018). As different learning outcomes may be expected according to the varied task parameter, some studies also compared two or more variable practice conditions (Cardis et al., 2018; Pacheco & Newell, 2018; Ranganathan & Newell, 2010b, 2010a). Here, the number of task conditions is not necessarily set before the experimentation as the variations can be applied by varying one or several task parameters along a continuous scale. Such manipulation can enable to either compare the effect of the variation of one parameter to the effect of another one (e.g., angle or distance from target, Pacheco & Newell, 2018), or the effect of different magnitudes of variations in the task parameter (e.g., large or small magnitude of change in the viscosity of a force field in a virtual shuffleboard task, Cardis et al., 2018). It should be noted that two studies mixed variable practice and contextual interference, so that participants trained different skills and experienced variations in task parameters within each skill (Bortoli et al., 2001; Vera et al., 2008). One of these studies examined the effect of four practice conditions (blocked or serial schedules with variations of the task or not) to train simultaneously underhand throwing to a target, quintuple jumping and hurdle running in children (Bortoli et al., 2001). The results showed that none of the groups improved performance in the throwing task, all the groups similarly improved performance in the running task and that the group with serial schedule with no task variations outperformed the other groups in the jumping task (Bortoli et al., 2001). These results suggest that these training conditions had different learning effects between skills and that varying simultaneously the skills and task parameters did not necessarily improve learning in comparison to practice conditions with fewer variations.

The changes in the task performance conditions can be scheduled to observe some progressivity across trials. Such schedule is used notably when applying sensorimotor perturbations. In this case, adaptations to the perturbations may be investigated by comparing sudden versus gradual (or incremental) application (Hussain & Morton, 2014; Klassen et al., 2005; Sawers & Hahn, 2013; Sawers et al., 2013). Gradual applications are not necessarily represented by an increase in the level of perturbation but can also relate to a decrease (X. Liu et al., 2016) or even to progressive changes in different directions throughout practice (e.g., changing a visuomotor rotation between +60° and -60°, Turnham et al., 2012). Progressive schedules are also applied to task difficulty. This manipulation is used notably to adapt the task difficulty to learners' skill level throughout practice. Indeed, the Challenge Point framework hypothesized that in order to maximize the gain from practice, an optimal level of functional task difficulty must be provided to the learners (Guadagnoli & Lee, 2004). Functional task difficulty corresponds to "how challenging the task is relative to the skill of the individual performing the task and to the conditions under which it is being performed" (Guadagnoli & Lee, 2004, p. 213). Therefore, increasing task difficulty progressively and automatically across trials was proposed (Y.-T. Liu et al., 2012) as well as adaptive schedules that are more sensitive to performance in previous trials were proposed. Those adaptive schedules could represent (i) a "win-shift lose-stay" (Simon et al., 2008), or (ii) an adaptive difficulty based on an error reduction learning rule and the performance in the last trial (Choi et al., 2008). The results showed that the effects of "win-shift lose-stay" schedules could not be differentiated from blocked and random schedules in acquisition and retention when learning key-press timing tasks (Simon et al., 2008), whereas the adaptive difficulty schedule clearly improved retention in comparison to a fixed difficulty practice condition in a pointing task with visuomotor rotation (Choi et al., 2008). Some studies also proposed that the difficulty level could be changed by manipulating the level of contextual interference during practice, lower contextual interference level being easier to face than higher levels (e.g., K. Jones & Croot, 2016; Keetch & Lee, 2007; Patterson et al., 2013; Porter & Magill, 2010).

Self-controlled practice was also proposed to give learners the opportunity to control the task difficulty in each trial (Andrieux et al., 2016, 2012; Y.-T. Liu et al., 2012). For example, the self-controlled practice in Y.-T. Liu et al. (2012) gave the learner the opportunity to choose to increase difficulty after successful trials or to decrease difficulty after failed trials in a rollerball task. Learners' control over task difficulty was shown to improve performances during acquisition and retention (Andrieux et al., 2016, 2012) and to optimize the ratio between success and failure during practice (Y.-T. Liu et al., 2012) in comparison to imposed schedules of task difficulty. Self-controlled practice is also proposed to give learners the opportunity to control their practice schedule when training a set of different task variations or movement skills (Hedges et al., 2011; Keetch & Lee, 2007). This was implemented to assess the scheduling strategies of the learners throughout practice, notably the way they choose to schedule the level of contextual interference throughout practice (Keetch & Lee, 2007). In these situations, self-controlled practice was also compared to more regular schedules such as progressively increasing difficulty (Y.-T. Liu et al., 2012) and blocked and random practice schedules (Keetch & Lee, 2007) to examine whether giving learners control over their task performance conditions help develop schedules that are more respectful of individual learning dynamics. The results showed that the given control helped learners to avoid continuous failure in task completion (Y.-T. Liu et al., 2012) and that the scheduling strategies showed important inter-individual variability but improved retention in comparison to imposed schedules (Keetch & Lee, 2007). Self-controlled practice was also used in the aim of enhancing learner's perception of autonomy (Lewthwaite et al., 2015; Wulf et al., 2018) in respect of the OPTIMAL (i.e., Optimizing Performance through Intrinsic Motivation and Attention for Learning) theory to motor learning, which focuses on the sociocultural, cognitive and affective context of human behavior (Wulf & Lewthwaite, 2016). This framework stresses that motivational and attentional factors play an important role in motor learning and learners' performance. Notably, the motor learning programs designed with respect to the OPTIMAL theory should (i) enhance learners' performance expectancies and (ii) support learners' fundamental need for autonomy and (iii) promote an external focus of attention (Wulf & Lewthwaite, 2016). The design of these studies usually compared the self-control group to another group following schedules yoked to those of the participants in the self-control group. This enabled to specifically assess the effect of the given opportunity to choose "when" to change the task condition, thus controlling the perception of autonomy (Lewthwaite et al., 2015; Wulf et al., 2018).

Some studies referring to motor learning frameworks changed multiple task parameters throughout practice in an unstructured way. Five studies used the Differential Learning framework (Hossner et al., 2016; James, 2014; James & Conatser, 2014; Pabel et al., 2017; Wagner & Muller, 2008). Differential Learning proposed that the addition of "noise" to movement patterns during practice would improve learning (Schöllhorn et al., 2006, 2012, 2009). In Differential Learning, the dynamics of motor learning is conceived as motion in a landscape (Schöllhorn et al., 2009). In this landscape, each position would correspond to behavioral dimensions and the elevation in the landscape to a performance score. Schöllhorn et al. (2009) hypothesized that the addition of noise in practice would foster the exploration of the landscape, thus helping learners escape local minima and discover the global minimum in the landscape. The noise is provided through variations in the task constraints that would act as stochastic perturbations in the learners' movement patterns. Thus, contrarily to the variable practice conditions presented previously, differential learning interventions appear to offer much more random exploration of the motor system. One study proposed to compare a differential learning group to another intervention group that would perform a more structured exploration of the task landscape (Hossner et al., 2016). This was achieved by changing the order of the task variants so that the magnitude of the change in the task conditions between trials was reduced. More precisely, the differential learning group experienced task conditions conceived with two variants from seven sources of variations taken randomly, whereas in the structural learning group, task conditions were also conceived with variants, but one was kept constant from trial to trial (Hossner et al., 2016). The results showed that reducing the differences in performance conditions between trials with the structural learning protocol led to greater performance improvement than a traditional learning protocol, which did not show statistical differences for the differential learning group, although the mean improvement was better (Hossner et al., 2016). These results suggested that a more structured learning protocol might better benefit learning than random variations in performance conditions.

One study proposed an intervention that referred to the Nonlinear Pedagogy framework (Lee et al., 2014). The aim was to learn to perform tennis forehand groundstroke to target by varying practice conditions such as the net height, the target area, the court size, the rules to achieve specific task goals and the outcome-focused instructions. However, the schedule of these variations is not described precisely in the method section. Based on concepts from the dynamical system theory and ecological psychology, Nonlinear Pedagogy central assumption is that learning dynamics is characterized by *non-proportionality* between the change in the practice task constraints and the effects on the learners' behaviors and performances, which reflects that learners follow individual pathways during practice (Chow, 2013; Chow, Davids, Hristovski, Araújo, & Passos, 2011). In this framework, motor learning interventions are designed to foster learners' functional movement variability (i.e., exploration of different movement solutions) as in the Differential Learning framework. However, nonlinear pedagogy stresses that this should be achieved using learning situations that are (i) representative of the performance context and (ii) developing relevant information-movement couplings (Chow et al., 2016). The lever that is used is the manipulation of constraints during practice to ensure functional movement variability, and to modify learners' attentional focus (Chow et al., 2016). In the context of the study captured in this review, the Nonlinear Pedagogy was used to learning a tennis forehand stroke (Lee et al., 2014). The results showed that participants in this practice condition demonstrated a greater variety of movement patterns in comparison to a prescriptive intervention in a post- and retention test (Lee et al., 2014). This supports the idea that encouraging learners' exploration helps the development of individualized and functional movement solutions.

The studies referring to motor learning frameworks (i.e., Differential Learning and Nonlinear Nedagogy) used a between-group study design that involved as control group, a group following a traditional, conventional, linear, low variability or repetitive practice (Hossner et al., 2016; James & Conatser, 2014; Lee et al., 2014; Pabel et al., 2017). Although the label of the groups differed, these groups referred to practice aiming at learners acquiring a common movement pattern based on an ideal technique, with the instructors providing feedback to correct the movement pattern during practice (Hossner et al., 2016; James & Conatser, 2014; Lee et al., 2014; Pabel et al., 2017). Two studies applying Differential Learning did not follow this design: one used a constant practice group as control with no ideal technique because it was a postural task (James, 2014) and the other was a case study with a high-level athlete using Differential Learning protocols and variable practice protocols to improve ball velocity and throw accuracy in a ball throwing task (Wagner & Muller, 2008).

In summary, this section highlighted the main theoretical backgrounds, which the reviewed studies referred to. On one hand, some of these theories originally proposed to implement variations in task conditions during practice with quite specific protocols (e.g., the contextual interference and the blocked versus random schedule comparison). On another hand, such protocols were implemented as a solution to test the hypotheses of other theories (e.g., the reviewed studies showed that the challenge point hypothesis could be tested with different forms of schedule of task variations). The final section of this review focuses more specifically on the testing performed in these studies to reveal the expected learning effects.

What Are the Expected Practice Effects?

Changing the task conditions during practice is expected to improve different aspects of learning. In the reviewed studies, the most common way to assess learning, that is, long-term change in behavior, was to use a retention test. Such test aims to assess the "memory" effect of practice. The retention test generally consists of performing the practiced task(s) after a period of rest without practicing. The delay between the end of practice and the retention test is variable across studies, but when practice takes place in only one session, the retention test is generally scheduled about 24h after practice. For example, when practicing multiple key-pressing sequences, the retention test consists of performing the different learnt sequences (e.g., Kim et al., 2018). One study, however, assessed retention one year after the practice of a basketball-shooting task with the specific aim of examining long-term retention and showed that variable practice improved retention in comparison to constant practice (Memmert, 2006). In addition to testing the trained coordination, one study also performed a scanning procedure (Maslovat et al., 2004). The scanning procedure aimed to assess the stability of the whole range of the possible coordination patterns (here, a bimanual coordination task). Indeed, the dynamical approach defines learning as the reorganization of the learner 's coordination tendencies, and supports that practice does not only affect the stability of the practiced coordination patterns, but may change the entire landscape of behavioral attractors of the learners (Schöner et al., 1992). In the context of the study captured in this review, the scanning procedure failed to differentiate post-practice the three tested groups (constant, blocked and random practice groups) (Maslovat et al., 2004) In some studies, retention was also assessed with a delayed transfer test to assess the memory effect.

Different forms of transfer were identified across the reviewed studies: skill transfer, transfer of learning and adaptation. In what follows, their definitions and modalities of evaluation are presented.

Skill transfer refers to the performance of the learnt skill in a new condition (Rosalie & Müller, 2012). This is the most frequently assessed type of transfer. Skill transfer is usually tested by changing the task parameter that was varied during practice. For example, in aiming tasks, if distance from target was varied, skill transfer is assessed performing the task from an unpracticed distance. However, the new value of the task parameter tested may be set within the range of its variations during practice, or beyond the range experienced during practice. For example, a study varied the target distance of a lever positioning task within three distances, 30, 60 and 90 cm with blocked and random practice, and confirmed the contextual interference effect in the transfer test with the target distance set at 75 cm (Perez et al., 2005). Another study varied the segment times in a key-press timing task during practice, and set the segment times in the transfer task at a superior value than those set during practice (C. H. Shea et al., 2001). Some studies also changed another parameter than the one varied during practice to create the transfer task. For example, some aiming tasks varied the location of the target during practice but increased the distance of the target in the transfer test (Fromer et al., 2016a, 2016b). The rationale for the design of these different transfer tests is not clear, although, setting a parameter beyond the values experienced during practice can often enable to assess transfer to a more difficult task condition (e.g., when increasing the distance from the target in an aiming task, or when increasing the speed of the treadmill in a locomotor task as in Hinkel-Lipsker & Hahn, 2017, 2018).

Another way to assess skill transfer was to vary the performance conditions also during the trials of the transfer test. For example, two studies using a virtual interception task performed two transfer tests after practice: one test with a fixed condition and one test with a variable condition (Ranganathan & Newell, 2010b, 2010a). These tests were not transfer tests for all the groups, as some of them experienced these conditions during practice, but at least one of the two tests was. In another study, a similar design was applied to an aiming task but this time, the two transfer tests involved the variation of two different task parameters (i.e., angle or distance to target) that corresponded to the variations experienced by the two practice groups respectively so that one test was a post-test and the second a transfer test (Pacheco & Newell, 2018). These study designs enabled to assess whether learning was specific to the practice condition and whether learning was generalizable to new practice conditions. One of these studies showed that, contrary to expectations, the fixed obstacle group showed better performances in the variable obstacle condition than the group experiencing this condition during practice (Ranganathan & Newell, 2010a). In contrast, the second experiment showed that transfer was specific to the practice condition when the target was varied instead of the obstacle (Ranganathan & Newell, 2010b). Similarly, one study labeled as a transfer test a test performed in serial order as the two groups practiced under a self-controlled or yoked schedule (Wu & Magill, 2011). This test revealed better transfer for the self-controlled group than for the yoked group (Wu & Magill, 2011).

The second form of transfer that was revealed was the transfer of learning, which can refer to practice facilitating performance of another movement skill than the one practiced (Magill & Anderson, 2017). For example, when practicing multiple movement skills during practice such as different key-pressing sequences, the transfer test aims to examine whether practice facilitates performance of a new key-pressing sequence[2] (e.g., Russell & Newell, 2007). In such context, the level of contextual interference was hypothesized to improve transfer of learning (and retention) by a greater elaboration and distinction of the information processing strategies used to perform in the different task conditions in random practice than in blocked practice (J. B. Shea & Morgan, 1979). An alternative hypothesis proposed that in random practice, learners forgot some parts of their action plan between trials due the interferences, which requires them to more actively reconstruct the plans

[2] In such situation, it may be argued that performance of a new key-pressing sequence is a change in the task goal. However, as the task and task goal are often confounded in key-pressing tasks, we considered that changing the sequence to produce corresponded to a different task. Thus, changing the sequence in the transfer test was considered as aiming to assess transfer of learning and not skill transfer.

during practice and would lead to a stronger action plan, hence facilitating retention. Consequently, the better transfer of learning from this random practice would be due to the similarity between the information processing demands when performing on the transfer task and during practice in the random condition (Magill & Hall, 1990).

Transfer of learning was also assessed from one coordination pattern to another. For example, one study showed that experiencing slips during a sit to stand task improved adaptability to slips in a walking task (Wang et al., 2011). It was also tested in a bimanual coordination task to examine whether practicing either 90° relative phase coordination pattern or both 90° and 45° relative phases transferred to 270°, but the transfer test failed to show a group effect (Maslovat et al., 2004). In these studies, the adaptations from practice are hypothesized to affect the motor system beyond the coordination patterns that was practiced as different coordination patterns may share some control mechanisms. Although the learning effects are expected primarily in terms of behavior rather than performance here, the results of this systematic review suggest that behavioral variables are less often collected than performance ones, although some frameworks (e.g., Differential Learning and Nonlinear Pedagogy) hypothesized that learning depends on behavioral variability or the development of the behavioral repertoire.

Transfer of learning was also the object of study in the Structural Learning hypothesis (which goes beyond the structural learning group proposed in Hossner et al., 2016). Braun et al. (2009) observed that practice in one task could facilitate learning in related tasks, and proposed a rationale for this “learning to learn” or meta-learning phenomenon. Considering that learners modify internal parameters that affect the mapping between the sensory inputs and the motor outputs, the authors argue that learners could also extract meta-parameters, which would be common to tasks sharing a common structure. This meta-parameter would be invariant across the tasks. Thus, extracting this invariant component would improve subsequent learning as the learners would only have to adjust the meta-parameter to the new task, reducing the exploration of the task space to the space along the meta-parameter (Braun et al., 2009). According to Structural Learning, the “learning to learn” phenomenon would appear subsequently to variable practice conditions only if the tasks experienced during practice shared a common structure (Braun et al., 2010). The main experimental paradigms used to test the Structural Learning hypotheses are pointing or reaching tasks performed with a visuomotor transformation. For example, Braun et al.

(2009) tested in the first experiment whether experiencing variable visuomotor transformations in a pointing task would facilitate the subsequent learning of new conditions of visuomotor transformations. The test consisted of learning consecutively three pointing tasks with a visuomotor rotation of +60°, -60° and +60° again, respectively. The results supported the Structural Learning hypothesis as learning of the three pointing tasks was facilitated for a group that followed practice with random rotation angle in comparison to a group following practice with random rotation and random linear transformation (the two groups had the same exposure to ±60° rotations) (Braun et al., 2009).

Finally, some studies assessed the generalization of practice within practice, which we labelled as adaptation. This was performed in two studies by examining the adaptation of participants to a task condition that differed from the main conditions. Thus, learners had to perform what was called "catch" or "probe" trials regularly interfering with practice (Braun et al., 2009; Mattar & Ostry, 2007). These enabled to examine whether the interventions facilitated the adaptation to this interfering condition acting as a control condition. In experiment 2 and 3 of Braun et al. (2009), the probe trials represented a consequent proportion of the practice period (30% of the trials) and mixed two conditions. Here again, the aim was to assess the Structural Learning hypotheses, as according to the visuomotor transformations experienced by the intervention groups, they were not expected to perform similarly in the different types of probe trials. The results supported the Structural Learning hypotheses as, in experiment 2, performance was better in probe trials where the visuomotor transformations shared their structure with those experienced by learners during practice (Braun et al., 2009). In experiment 3, the rotation was null in probe-trials, but learners showed exploration in the direction of the visuomotor transformations they were exposed to during practice, supporting that they learned the structure of their practice condition (Braun et al., 2009).

In summary, this section highlighted that retention test remained the most common way to assess learning. However, retention test was not necessarily involving the practice task, as retention could also be evaluated with delayed transfer test or (once) with a delayed scanning procedure. Transfer tests are also frequent, but as highlighted in this section, "what" is transferred can differ importantly across studies. Therefore, we proposed to differentiate the transfer tests according to their purpose: adaption, skill transfer or transfer of learning.

Conclusion

This review showed that the methods used to provide varying tasks performance conditions demonstrate an important diversity regarding the investigated tasks, sources of variations, the scheduling of the task conditions and the design of the tests performed to examine the effects of practice. This review could however highlight some recurrent hypotheses, methods and purposes associated to practice with variations in task conditions that would help set up future learning protocols. Different theories hypothesized that variations in task conditions during practice would facilitate transfer and retention. In contrast, the results of some studies also suggested that the groups experiencing the highest level of variability in their practice conditions were not necessarily those showing the better learning outcomes. Recent perspectives have also proposed learning protocols that tend to be learner-centered. They develop practice conditions fostering learner’s exploration of functional movement solutions or practice conditions that are more respectful of individual learning dynamics by (i) taking into account learners’ progression or (ii) giving learners some control over their practice conditions.

Supplementary Information

Table 5. List of the keywords

Learning	Movement	Variable Practice Conditions	Test
Learning Acquisition Pedagogy Intervention Practice Training	Action Movement Motor Coordination Perceptual-motor	Variable Exploration Variability Differential Perturbation Novelty Random Blocked Constraints Nonlinear Self-control	Test Transfer Retention Recall posttest

Table 6. Search performed in PubMed database

PubMed Search
((learning[Title/Abstract] OR acquisition[Title/Abstract] OR pedagogy[Title/Abstract] OR intervention[Title/Abstract] OR practice[Title/Abstract] OR training[Title/Abstract]) AND (action[Title/Abstract] OR movement[Title/Abstract] OR motor[Title/Abstract] OR coordination[Title/Abstract] OR perceptual-motor[Title/Abstract]) AND (variable[Title/Abstract] OR exploration[Title/Abstract] OR variability[Title/Abstract] OR differential[Title/Abstract] OR perturbation[Title/Abstract] OR novelty[Title/Abstract] OR random[Title/Abstract] OR blocked[Title/Abstract] OR constraints[Title/Abstract] OR nonlinear[Title/Abstract] OR self-control[Title/Abstract]) AND (transfer[Title/Abstract] OR retention[Title/Abstract] OR recall[Title/Abstract] OR posttest[Title/Abstract] OR test[Title/Abstract])) AND ("2000/01/01"[PDat] : "3000/12/31"[PDat]) AND Humans[Mesh] AND English[lang]

Table 7. Search performed in Embase database through Cochrane library

Cochrane library / Embase search
((learning OR acquisition OR pedagogy OR intervention OR practice OR training) AND (action OR movement OR motor OR coordination OR perceptual-motor) AND (variable OR exploration OR variability OR differential OR perturbation OR novelty OR random OR blocked OR constraints OR nonlinear OR self-control) AND (transfer OR retention OR recall OR posttest OR test)):ti,ab,kw" with Publication Year from 2000 to present, with Cochrane Library publication date from Jan 2000 to present, in Trials

Aims and Hypotheses

Summary of the Reviews

The literature review showed that goal directed behaviors emerge from the reciprocity between the capabilities and characteristics of the performers and the properties of the environment. Indeed, performers act using the information generated by their own movements, creating an information-movement coupling, which enables them to dynamically adapt behavior to environmental properties. In **Chapter 1**, the review of the literature showed that with skill learning, performers learn (i) to use more reliable information to guide their actions (i.e., attunement) and (ii) to scale information to their actions capabilities (i.e., calibration), which appears to foster skill transfer when information can be retrieved in the new performance context (Fajen & Devaney, 2006; Huet et al., 2011). Therefore, in respect to the direct couplings between information and movement, the learners' exploratory activity should also demonstrate qualitative changes with skill learning that support skill transfer to performance contexts different from the learning contexts.

Regarding change in exploratory activity, **Chapter 2** aimed to review more specifically the literature on change in gaze behavior with skill learning. Most of the studies used cross-sectional design to compare samples with different skill levels (e.g., experts vs. novices or adults vs. children) but within performers' changes in gaze behaviors in relation to body movements with practice were more rarely investigated. However, studies showed that task requirements affected the gaze behavior to maintain proficiency. First, task goal constrains the search behavior of the gaze: even in cluttered environments, performers rarely looked at areas that are irrelevant for task completion in their surroundings. Second, as central vision offers greater acuity than peripheral vision, online guidance of movements by the gaze is used when accuracy is required. However, whenever possible, performers guide movements with peripheral vision to free central vision to be able to proactively search for future performance constraints. The differences between novices and experts are that novices' gaze moves between a larger number of areas of interest than experts and that the timing of their gaze movements in relation to body movements or events can be detrimental to guide movements. Therefore, perceptual-motor skill transfer may reside in conceiving practice conditions helping learners to develop gaze activity that can be used in different performance contexts to facilitate adaptation of movements to the new set of constraints.

The **Chapter 3** aimed to review the methods used to provide variability in the practice conditions and the underlying theoretical backgrounds and associated hypotheses. The results of the systematic review of the literature showed that experiencing task variations during practice was proposed by different motor learning theories to enhance transfer and retention of learning. Transfer and retention were assessed mainly by means of performance, but the behavioral changes that supported skill learning and transfer were less investigated. This may be explained notably by the dominant use of laboratory tasks involving low complexity movements. Studies also showed that the rate at which learners experience the different task variations within practice and the time given with each task variation are highly variable across studies. However, different solutions were proposed to adapt schedule of task variations to the individual learning dynamics. Notably, self-controlled practice schedules appear more effective than imposed practice schedules to promote skill learning. The main reasons raised by the studies are that the given control promotes an autonomy supportive learning environment and that it enables to challenge participants at an optimal level in relation to their skill level throughout practice.

Objectives and Hypotheses

The main objective of this thesis is to examine the changes in exploratory activity that support skill learning and transfer. In this aim, the changes in the individual performances, gaze behavior and behavioral flexibility are examined, in function of practice and performance contexts. Moreover, this thesis investigates whether the infusion of variability in practice with imposed or self-controlled practice schedules of task variations would foster transfer of skill by developing learners' behavioral flexibility and guiding learners' exploratory activity. The main hypothesis is that experiencing interactions with various performance contexts during practice would foster the development of exploratory activity, therefore facilitating the transfer of skill to novel performance context.

In a first experiment (**Chapter 4**), the objectives are to investigate the modifications of learners' visual and haptic exploratory activity with practice and to determine to what extent the acquired perceptual-motor skill and the learners' exploratory activity would transfer to environments presenting novel properties. This experiment involves the manipulation of the performance context to examine whether participants can maintain performance in the different contexts.

In a second experiment, the first objective is to examine whether infusing variability in practice would foster skill learning and transfer. The confrontation of learners to new climbing routes would encourage the discovery of new behavioral solutions, which should develop learners' behavioral flexibility. It is also expected that the confrontation to new routes would guide the development of exploratory activity facilitating adaptation to new performance contexts. The second objective is to investigate whether variable practice conditions could be optimized by giving learners the opportunity to control the frequency of variations in the task and by extension the amount of total variability encountered during practice. Given that learning dynamics differ according to individual-environment relationship, self-controlled practice would offer practice conditions that are more respectful of the individual learning dynamics by enabling participants to better exploit their relationship to the different learning contexts. In this experiment, the behavioral transformations related to variable and self-controlled practice are investigated at three levels.

The first level is the behavioral flexibility of the participants (**Chapter 5**). Two hand coordination patterns (hand alternation and hand repetition) and their flexibility are assessed by manipulating task constraints in a pre-, post- and retention test. We expect that on pretest, the task constraints would conflict with the participants' repertoires in conditions where hand repetition is expected or where the holds layout competes with hand alternation. Then, we expect different learning outcomes for our three learning groups. First, the learners in the constant practice condition would demonstrate low flexibility with the two coordination patterns in posttest and retention due to the lack of movement variability during practice, whereas the two groups with task variations would show more ease in adapting the two patterns to the different sets of task constraints. Second, the self-controlled group would show less interindividual variability in the learning outcomes in comparison to the group experiencing imposed task variations, as all the learners in this latter group might not have sufficiently stabilized the new behavioral solutions in their repertoires. Thus, we expect that a larger proportion of participants in the self-controlled group would show improved behavioral flexibility in comparison to the group with imposed task variations.

The second level is the performance dynamics of learners (**Chapter 6**). The first aim is to test whether practicing on task variations would affect performances and behavioral variability. We expect that experiencing task variations during practice would increase behavioral variability in comparison to constant practice, which would improve the learning rate (faster improvement in performances) and improve performance on a transfer test. A second aim is to examine whether outcomes of the practice on task variations can be improved by giving participants the opportunity to control the amount of practice on each task variation in comparison to participants for whom variations is imposed. We expect that learners would benefits from self-controlled practice schedules in comparison to imposed practice schedules with greater improvements in performance during practice and on transfer task.

The third level is the visual exploratory activity (**Chapter 7**). Climbing locomotion requires that the visual system guides ongoing movements and seeks for future opportunities for action. The main hypothesis is that this dual demand may be better responded to with confrontation to task variations during practice. We expect that the imposed schedule of task variations would invite more proactive gaze behaviors than constant practice on both the learning and transfer performance contexts. The gaze behavior developed with constant practice may not be best adapted to climbing a new route as learners may become too specifically attuned to the learning context, where exploration will likely reduce after extended practice. Second, we expected that the more optimal ratio between exploration and exploitation of the different task variations when following a self-controlled practice schedule would translate into a gaze behavior that is less proactive than imposed schedules in learning and transfer performance contexts, suggesting a heightened skill in coupling information to movements.

Climbing as Research Vehicle

Indoor climbing appears as a suitable support activity to investigate these research questions. Indeed, climbing is a physical activity where the task-goal is to reach the last handhold of the climbing route (usually the highest one). Quadrupedal locomotion must be performed on a vertical plane, requiring that climbers apply forces with the extremities of their limbs on holds to progress on the climbing route against gravity. The holds properties can be changed, such as their size, shape and orientation which directly affect how climbers can use the holds with their extremities. For example, a large hold size may enable grasping pattern with the whole hand or the entire sole of a foot whereas smaller holds would require climbers to apply forces with only few fingers or toes. Therefore, climbing require performers to adjust the way they use the holds and apply forces to be able to move from hold to hold while maintaining balance (Quaine, Reveret, Courtemanche, & Kry, 2017).

The use of the limbs' extremities and notably the fingertips to produce forces generate important stress to forearm muscles. In particular, isometric contraction of several minutes duration can be observed and the induced fatigue can be detrimental to movement performance and postural stability on the wall (Vigouroux, 2017). Therefore, developing climbers' perceptual-motor skills and notably their route finding skill would improve their performances. Route finding skill was characterized by previous studies showing that experts climbers were able to perceive the opportunities for actions offered by the climbing route properties, whereas novices focused on physical properties of the holds (Boschker, Bakker, & Michaels, 2002; Pezzulo, Barca, Bocconi, & Borghi, 2010). Thus, route finding skill consists of being able to perceive how to use the holds of the route to chain the climbing movements smoothly (i.e., by limiting the movements of the center of mass, Cordier, France, Pailhous, & Bolon, 1994). This skill highlights that in climbing, perception of opportunities for actions depends on the previously performed action as posture and limbs availability restrains the landscape of possible actions to reach the next hold (Seifert, Dicks, Wittmann, & Wolf, 2021). This nestedness in the affordances of a climbing route illustrates that behavioral dynamics in climbing build on the functionality of the climber-route relationship, thus the ability of the climbers to satisfy environmental and task constraints in relation to their action capabilities (Araújo et al., 2017; Davids, Araújo, Seifert, & Orth, 2015). As indoor climbing allows the manipulation of environmental properties that directly impact the locomotion of climbers (Orth, Davids, & Seifert, 2018; Seifert et al., 2015), the transfer of route finding skill to new performance contexts that differ from the learning environment can be assessed by setting up a route that was not encountered during the learning context.

Chapter 4: Exploratory Activity in Learning and Transfer

Introduction

Throughout practice, learners discover what they can do and how they can do it to successfully reach their task-goal. According to the ecological approach to perception and action, as learners practice, they attune to relevant information for actions that, when it is scaled to their action capabilities and body size, enables them to accurately perceive opportunities for action, also called affordances (Fajen, 2007; Gibson, 1979/2015). Yet information has to be generated and picked up actively by the perceptual systems through changes in the body orientation, movements of the eyes, surfaces touching etc. (Gibson, 1966). This exploratory activity produces information that is used to guide the individual's action (Gibson, 1966, 2015). In this view, exploratory activity links the information to the control of movements (Gibson, 1979/2015; Reed, 1996). It is conceived as a skill that is learned as individuals get better at discriminating their surroundings (Gibson, 1966; Gibson & Gibson, 1955). Thus, the adaptive control of movements requires (i) adequate exploratory actions and (ii) differentiation of the relevant information structures (Adolph et al., 2000, 2001). In the present study, we used a climbing task to investigate how individuals change their exploratory activity as they learn to exploit the properties of their learning environment (i.e., the holds on the climbing wall) and to examine to what extent these changes can be transferred to environments presenting novel properties.

Changes in Visual and Haptic Exploration in Climbing and Locomotor Tasks

In studies about perceptual-motor control and learning in climbing (Nieuwenhuys, Pijpers, Oudejans, & Bakker, 2008; Orth, Davids, Chow, Brymer, & Seifert, 2018; Pijpers, Oudejans, & Bakker, 2005; Pijpers, Oudejans, Bakker, & Beek, 2006; Seifert et al., 2018) and about the broader topic of the development of locomotion (Adolph & Franchak, 2017; Franchak et al., 2011; Kretch & Adolph, 2017) visual and haptic exploration have been investigated as key modes of exploration for finding affordances. In climbing studies, climbers use exploratory hand movements to better perceive (i) whether a handhold is within reaching distance and (ii) how to best grasp the handhold (Orth, Davids, & Seifert, 2018; Pijpers et al., 2006; Seifert et al., 2018). Haptic exploration of a handhold is an engaging modality because the climbers have to free one limb that would normally be used as a support. However, haptic information also informs and reassures them about how the hand and body should be placed and helps them to simulate a grasping pattern for using the handhold as a support. Recent studies have shown that climbers perform exploratory hand movements less frequently as they attune to the affordances of the holds with practice, and that less experienced climbers rely more than skilled climbers on exploratory hand movements even when they are discovering a new route (Orth, Davids, & Seifert, 2018; Seifert et al., 2018). These results suggest that with experience and practice, the information obtained from a distance using the visual system becomes sufficient for climbers to perceive and chain their movements on the route. Only one study investigated the changes in the gaze behavior of climbers during practice (Button et al., 2018), showing that they performed fewer fixations during the ascents over the six trials of the protocol, although they maintained their search rate (i.e., the number of fixations per seconds) (Button et al., 2018). Yet, no study has investigated the effect of practice on both hand movements and gaze behaviors in climbing. A joint analysis of the two was only performed in a study designed to assess the effect of anxiety on the exploratory activity during a climbing task (Nieuwenhuys et al., 2008). It revealed that the anxiety induced by an increase in climbing height drove the climbers to less efficient climbing behavior, which was suggested by the increase in exploratory hand movements, longer grasps on the handholds, and longer fixation durations. Also, this study showed that the fixations occurring during hand movements (categorized as performatory fixations) had mean durations that were about three times longer than the other fixations (categorized as exploratory fixations) but that the exploratory fixations were about two times more frequent than those that were performatory. These results indicate that when climbers are looking for information about affordances, either in the first learning sessions or in anxiety conditions, they display high exploratory activity, but as they better attune to the affordances of the climbing routes, this exploratory activity tends to decrease and exploratory hand movements even seem to disappear.

In developmental psychology, studies have shown that children also prefer touch and vision as they search for ways to match locomotor actions with a bridge or a slope (Adolph, 1995, 2008; Adolph et al., 2000). The results of these studies led to the ramping-up hypothesis to describe the organization of exploratory actions (Kretch & Adolph, 2017). According to this hypothesis, modes of exploration are organized in space and time so that individuals progressively use more engaging modes to perceive whether and how to cope with an obstacle (e.g., a bridge or a slope). Visual exploration is usually the first modality used for information pickup, and if the information is insufficient, haptic information may be sought. The children in Kretch and Adolph' study (2017) used exploratory touch (with hands or feet) to confirm the visual information (e.g., regarding bridge width) or to obtain information that was not available from a distance (e.g., information about ground rigidity or surface). However, neither the mode (visual or haptic) nor the quantity (number of actions and durations) of explorations predicted task success, although experience with the task did (Kretch & Adolph, 2017). For example, these children required experience with the mode of locomotion to better use the picked-up information and improve decision-making. The children with less experience used touch in both safe and unsafe (e.g., wide and narrow bridge) conditions, demonstrating (i) their difficulty in exploiting both visual and haptic information and (ii) a lack of sensitivity to their action capabilities (Kretch & Adolph, 2017). Overall, these results show that the number and/or duration of exploratory actions decrease with learning and development, thus that the search for information declines. It also suggests that as individuals better differentiate information and become more sensitive to their action capabilities, they become more skilled at accurately revealing opportunities for action in their environment.

These results in studies about climbing and the development of locomotion suggest that two functions of exploratory activity can be discerned and applied to skill learning. The first function is to search for and discover available information so that the learners progressively differentiate the relevant information for task completion (Gibson, 2000; Gibson & Gibson, 1955). This function of exploratory activity can thus be characterized by a high amount of actions of the perceptual systems as the learners discover the properties of their task environment and the possibilities for action that they afford (Gibson, 1966). Such exploratory activity can appear to lack in goal-directedness because the learners may attend to many areas in the environment (e.g., with touch or visual search), but this is necessary to progressively raise new possibilities for action and reorganize the information-movement coupling more specifically to the constraints of the task environment (Adolph & Robinson, 2015; van Dijk & Bongers, 2014).

The second function of the exploratory activity appears with experience in the task and is used to effectively reveal, pick up and exploit information for affordances (van Dijk & Bongers, 2014). Although the learners are now attuned to the possibilities for action that their task environment offers, they still have to continuously scale their movements to the unfolding dynamics of their relation with this environment. This process is called calibration (Davids et al., 2012; Fajen et al., 2008) and has been suggested to be characterized by a gain in the goal-directedness of the exploratory activity. Essentially, the primary role of the exploratory activity is now to reveal and exploit relevant information for task achievement, whereas the discovery role of the exploratory activity predominated at the earlier learning stage (van Dijk & Bongers, 2014). Therefore, in the present study, we want to examine whether this assumption can be observed when learning a climbing task. That is, learners' exploratory activity should not be only characterized by a decrease in the amount of exploratory actions, but it should also reorganize so that their exploratory activity becomes better embedded in the continuous flow of actions by gaining in goal-directedness.

Transfer of Learning in Ecological Psychology

With learning, exploratory activity should become a skill by enabling individuals to probe and exploit relevant information in different environmental contexts to adapt their behavior accordingly (Adolph, 2008; Gibson, 1966).The second question raised in this paper is to what extent can climbers transfer their perceptual-motor skill and exploratory activity to an environment with different properties (i.e., a different climbing route)?

In ecological psychology, the transfer of learning implies the transfer of both attunement and calibration to the new context. The transfer of attunement, has been presented as the ability to detect information with different action systems (de Vries, Withagen, & Zaal, 2015) or as the ability to detect and exploit reliable information to guide action in different contexts of performance (Huet et al., 2011; Smeeton, Huys, et al., 2013; Smith et al., 2001). For example, in a tennis anticipation task, the participants trained to attend to reliable informational movement patterns of a stick-figure player's shot. They were able to transfer their ability to anticipate the direction of the shot even in conditions where the informational movement patterns on which they had focused their training (the arm and racket movement of the stick-figures) were neutralized, with only other body region movements remaining available (Smeeton, Huys, et al., 2013). The conclusion was that when the learners' attention during practice was directed toward reliable information, this attunement facilitated the transfer of the perceptual motor skill to new contexts, even when the available information was less reliable.

The transfer of calibration has been studied through two processes (Brand and de Oliveira, 2017). The first is called recalibration and refers to the rearrangement of the perception-action coupling (i.e., the rescaling of information) following a disturbance that makes the coupling inaccurate. The perceptual-motor system needs to be recalibrated when

(i) an individual's action capabilities or body dimension changes over short (e.g., by wearing an apparatus like ankle weights or walking on stilts) or longer (e.g., with development or training) timescales or (ii) perception is altered (e.g., by wearing prism glasses). The second process is the transfer of calibration, which occurs when the rearrangement of the perception-action coupling in one action transfers to another action. For example, although children are able to perceive the cross-ability of a slope when they crawl, when they start walking they will engage in walking on impossible slopes unless they have sufficient experience with this new mode of locomotion (Adolph, Tamis-LeMonda, Ishak, Karasik, & Lobo, 2008; Kretch & Adolph, 2013). These findings suggested that the transfer of calibration was possible only when the children were sensitive to the boundaries of their action capabilities in the new mode of locomotion. Brand and de Oliveira (2017), noted that recalibration and transfer of calibration required exploratory activity that was effective only if (i) the individuals were attuned to the relevant information, (ii) the source of information was still available after disturbance, and (iii) the perceptual-motor skill had been thoroughly learned.

In sum, the attunement of the perceptual-motor system to reliable information appears to be a prerequisite for any form of transfer of learning from one context to another. Then, if this prerequisite is respected, the quantity of exploratory activity necessary to adapt the actions to the new context depends on the intensity and nature of the disturbance.

Current Study

An indoor climbing task was chosen for this study. Climbers need to learn a route-finding skill. That is, they have to perceive how to use the holds on the climbing route so that they limit the movements of their center of mass during ascents and chain their climbing movements fluently (Cordier, France, Pailhous, & Bolon, 1994; Seifert et al., 2018). Route-finding skill highlights a particularity of climbing, which is that perceiving an opportunity for action on the route depends on the climber's previous action. For example, grasping a handhold affects the availability of a limb for the next movement and handhold orientation affects the entire body posture (Seifert, Boulanger, Orth, & Davids, 2015). This illustrates how nested the affordances in climbing tasks are, as the perception of one action during the ascent is accurate if the climbers also perceive the changes in their action capabilities due to the previous action (Wagman et al., 2018; Wagman & Morgan, 2010). Essentially, if the properties of the climbing route are changed, it may affect the whole chain of movement. For this reason, acquiring exploratory skill that can be transferred and used to perceive how to chain movements on new routes is quite valuable in lead climbing and bouldering, two of the three competitive indoor climbing disciplines where performers are often confronted with new climbing routes.

As indoor climbing tasks allow the manipulation of environmental properties that directly impact the locomotion of climbers (Orth, Button, Davids, & Seifert, 2016; Seifert et al., 2015), the transfer of route-finding skill can be assessed by changing the environmental properties of the learning route. More specifically, the literature has shown that climbers need to adapt differently according to the changes: (i) increasing the distances between handholds requires more force and amplitude in the climbing movements (Testa, Martin, & Debû, 1999), (ii) changing the handhold orientation requires a modification in the whole body posture to use the handholds (Seifert et al., 2015), and (iii) changing the handhold shape requires different grasping patterns and close attunement to the functional properties of the handholds (Button et al., 2018).

Regarding our study objectives, we first hypothesized that the participants would learn how to pick up and exploit relevant information for action on the learning route through attunement and calibration of their perceptual-motor system, while they discovered climbing movements that fit both the route properties and their action capabilities. Their enhanced route-finding skill (i.e., their ability to perceive and chain climbing movements) would lead to greater climbing fluency (i.e., lower entropy of hip displacement), while the ability to explore efficiently would be revealed by (i) a decrease in the quantity of exploratory actions (i.e., fewer exploratory hand movements and a decrease in the gaze search rate) and (ii) more goal-directed gaze behavior (i.e., lower visual entropy) as exploration would be increasingly used to guide actions rather than searching for affordances.

The second hypothesis was that, the transfer of route-finding skill to routes with modified properties would be revealed by similar improvements in the fluency scores on the learning and transfer routes (i.e., similar decreases in the entropy of the hip displacement in the posttest). The transfer of exploratory skill would also be revealed by similar changes in gaze and haptic behaviors on the learning and transfer routes. We expected that learners would show better transfer when the new properties of the climbing route invite learners to adapt their climbing movements with low-order behavioral changes (i.e., superficial refinement at spatial or temporal level, like amplitude of movement), than when the new properties invite high-order behavioral changes (i.e., deep reorganization at the motor coordination level, like postural regulation and coordination between limbs) as the disturbance of the information-movement couplings would be more important in the latter condition.

Method

Participants

Eight students volunteered to participate in the study but one dropped out after the first learning session. The remaining seven participants (2 males and 5 females, mean age 18.4 ± 0.8 years old, mean height 167.7 ± 5.3 cm, mean weight 57.4 ± 5.7 kg, mean arm span 165.2 ± 7.6 cm) had a grade 5C skill level in rock climbing on the French Rating Scale of Difficulty (F-RSD), which corresponds to an intermediate level (Draper et al., 2015). They had been climbing for about 2 years for 3 hours per week. All had normal or corrected-to-normal vision.

Protocol

The learning protocol consisted of 13 climbing sessions. Ten of them were learning sessions during which the participants always climbed the same route, which was the Control route. They had three trials per learning session and their task-goal was to "*find the way to climb the route as fluently as possible, avoiding pauses and saccades.*" After each learning session, they received feedback on their hip trajectories and fluency scores[3]. The

[3] The feedback was designed to give participants information about their climbs' outcomes and to guide learning. The aim was to encourage the participants to explore new ways to climb the route and fluently chain their movements to lower the fluency scores as much as possible without explicitly telling them how to improve. Thus, we encourage with this feedback an external focus of attention (Peh et al., 2011; Wulf & Shea, 2002). More specifically, participants received by e-mail the feedback with pictures of the harness light trajectories on the three climbs of the session (one picture/climb) and the corresponding values of three fluency indicators labeled as spatial, temporal and spatiotemporal fluency. On the second session, the feedback of the first session was described and explained to the participants. They were told that the line corresponded to the trajectory of the light on their harness during the climb and that the more direct the trajectory is, the better (i.e., the lower) the spatial fluency score would be (the geometric index of entropy, Cordier et al., 1994). The temporal fluency score was described as the percentage of the climbing time spent immobile (Orth et al., 2018) and the spatiotemporal score (the jerk of hip rotation, Seifert et al., 2014) as the amount of saccadic movements during the climb. They were also told that their aim is to lower these scores as much as possible throughout the practice sessions. Before each session, the experimenter asked

learning sessions were distributed over 5 weeks, with two climbing sessions per week. Participants also attended three test sessions: a pretest before the start of the learning sessions, a posttest the week following the learning sessions, and a retention test 5 weeks after the posttest. During the test sessions, they had to climb four routes in random order. One of them was the Control route and the three others were transfer routes. The transfer routes had the same number of handholds as the Control route (i.e., 16), but they differed on half the handholds as follows: (i) the distance between handholds was increased but remained less than the participants' armspan, (ii) the handhold orientation was changed (i.e., it turned 90°), or (iii) the handhold shape was changed. The manipulations are illustrated on **Figure 4**. The three transfer routes were respectively termed the Distance route, the Orientation route and the Shape route. As shown in **Figure 5**, the Control route was divided into four areas composed of four handholds and the modifications to create the transfer routes were located in two of these areas: the Distance route differed in areas 1 and 4, the Orientation route in areas 2 and 4, and the Shape route in areas 1 and 2. Two qualified route-setters rated the four routes as 5B+ on the F-RSD (Draper et al., 2011), which indicated slightly under but close to maximal difficulty for the participants. All the climbs were top-roped, which meant that the safety rope was anchored at the top of the climbing wall. This safety mode was chosen as an attempt to reduce the potential effects of higher anxiety during ascents (Hodgson et al., 2009). Before each trial for all sessions, the participants had 2 minutes to preview the route.

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the participant if they received and looked at the last feedback, and if they did not, the experimenter showed the feedback before starting the new session.

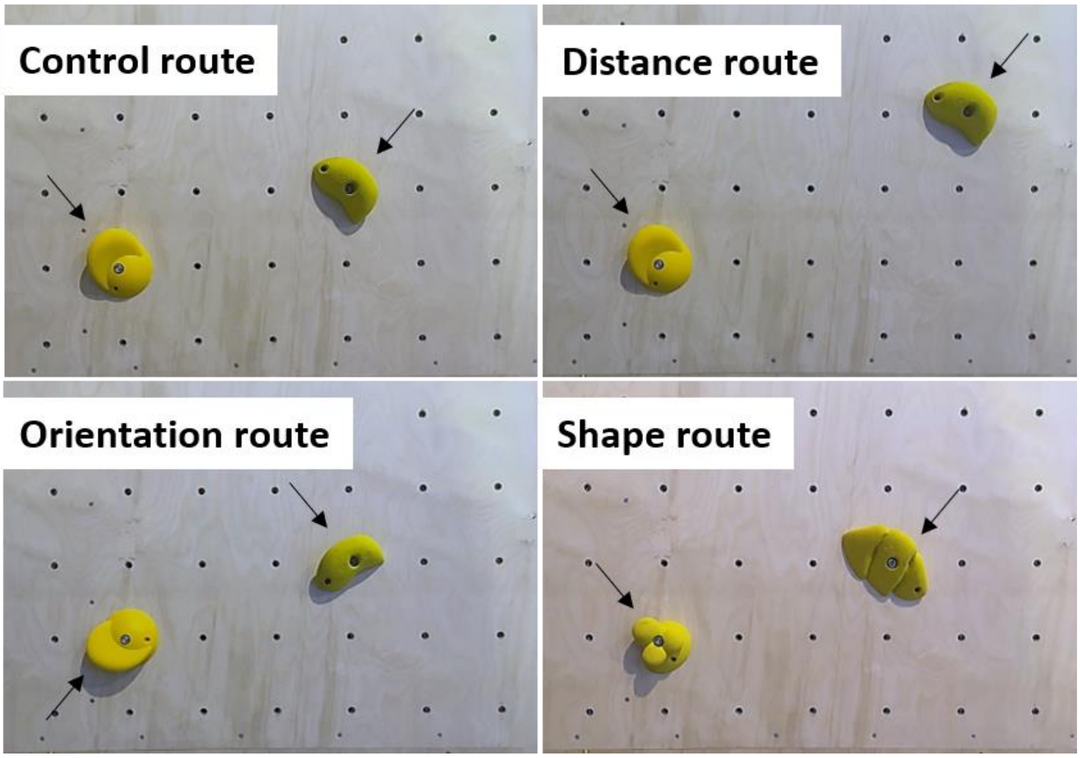

Figure 4. Manipulation of the handholds to create the transfer routes.
The arrows indicate the preferential grasping enabled by the handhold.

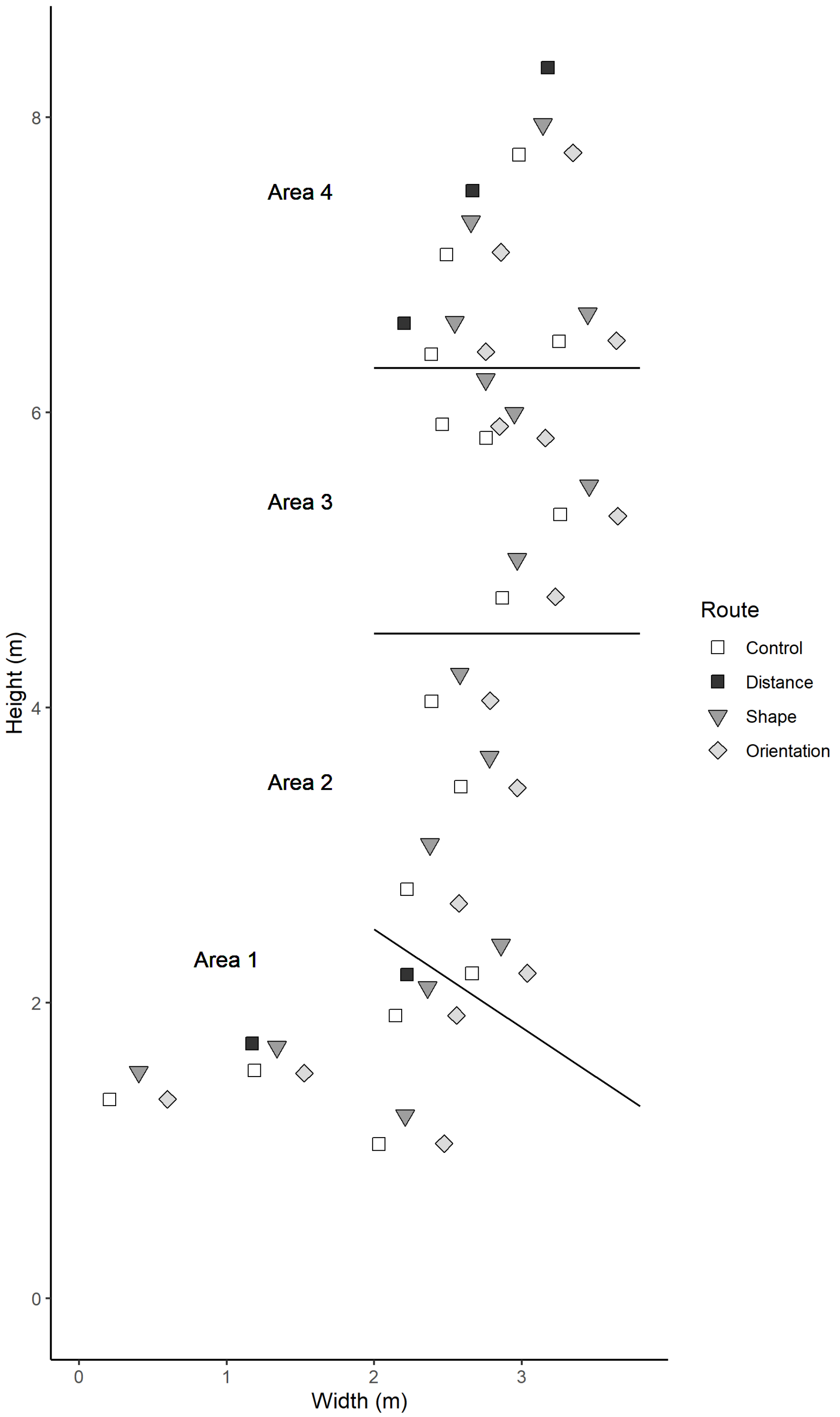

Figure 5. Location of the handholds for the four routes in the test sessions.
The shapes and colors refer to the four routes climbed during the test sessions. Only the five handholds of the Distance route that were moved are visible because the other handholds share the same locations as the handholds of the Control route.

Measurement of Performance and Exploratory Hand Movements

On each ascent, the participants wore a harness with a light placed on the back. Ascents were filmed at 24 fps on 1920x1080 pixel frames with a GoPro Hero 3 camera covering the entire route from 5.45 m and at a height of 5 m. The harness light was tracked on video with Kinovea 0.8.25 software to obtain coordinates of hip trajectory projection on the 2D wall. The camera lens distortion was compensated by importing the intrinsic parameters of the camera and the video perspective was corrected using a manually set grid-based calibration on this software. The videos of the climbs were also used to code the exploratory hand movements of the participants (see the subsection Exploratory Hand Movements in the section Dependent Measures for more details).

At the beginning of each trial, the participant stayed immobile with two hands on the first handhold and one foot on the first foothold. The start of the trial began when the second foot left the ground. The trial ended when the participants held the last handhold with their two hands.

Measurement of Gaze Behavior

Although visual exploratory activity is not limited to eye movements, we chose to investigate the participants' visual exploration through their gaze behaviors measured with a mobile eye-tracking system. In our climbing task, their head or body movements were not limited. In such conditions, the gaze locations obtained with the mobile eye-tracking system reflect the visual exploratory activity that resulted from the participants' eye, head and body movements (Franchak, 2019).

On each ascent, the climbers wore SMI eye tracking glasses (SensoMotoric Instruments GmbH, Teltow, Germany) that recorded gaze behavior at 60Hz. This binocular system is reported to have an accuracy of 0.5° of visual angle (https://imotions.com/hardware/smi-eye-tracking-glasses/, see also Cognolato, Atzori, & Müller, 2018 for a comparison with other eye-tracking system). It needs a three-point-based calibration, which was performed before each trial. To mark the beginning of each trial, the participant had to fixate on a target at the start of the route placed above the first handhold. The end was assumed when the participants fixated the last target placed above the last handhold.

Eye fixation locations on the wall were obtained with the eye tracking analysis software, SMI BeGaze (version 3.7.59, SensoMotoric Instruments GmbH, Teltow, Germany).

Fixation events were determined with the SMI Event detection algorithm as periods during which the point of regard velocity was (i) below 8°/s or (ii) below 100°/s and the velocity skewness (i.e., the ratio between the velocity mean and median over a 5-sample window) was below a value of 5. In addition, fixation events that lasted less than 50ms were not considered. Then, we classified each fixation location into a specific area of interest (i.e., AOI). A 20-cm circle around each hold of the climbed route was considered as an AOI of the route and the rest as the last AOI (i.e., the wall).

Dependent Measures

Performance

The coordinates of the hip trajectory were used to compute the geometric index of entropy (i.e., GIE), which assesses the complexity of the hip trajectory (Cordier, Mendés France, et al., 1994). GIE was designed as a global measure of performance that reflects the degree of coherence in perception-action couplings (Cordier, Mendés France, et al., 1994). Using the length L of the hip trajectory and the perimeter c of the convex hull around the trajectory, GIE (H) is calculated with the following equation:

$$H = \log_2(\frac{2L}{c})$$

Therefore, a low GIE reflects a smooth hip trajectory, indicating that the climber is sensitive to the environmental constraints, whereas a high GIE reveals a random trajectory that might be linked to the need to search the environment in order to keep progressing on the route.

Exploratory Hand Movements

The number of exploratory hand movements was counted by an expert climber for each trial of the test sessions. The expert climber watched the videos captured with the GoPro camera and coded the number of exploratory movements and the corresponding handholds on an Excel sheet. In accordance with Pijpers et al. (2006), an exploratory movement was defined as a participant's hand touching or grasping a handhold without using it to progress on the route.

Gaze Behaviors

In order to assess the quality of the gaze-tracking data, the percentage of samples captured during the climbs was measured for each trial. Thus, the measured tracking ratio corresponded exactly to the period used to investigate the participants' gaze behaviors.

The gaze behaviors were assessed with three commonly used search rate measures: (i) the mean duration of fixations, (ii) the number of fixations, and (iii) the number of AOI fixated during each ascent (Dicks, Button, et al., 2010; Vaeyens, Lenoir, Philippaerts, & Williams, 2007). In addition, we calculated the relative duration of fixations on AOI, which was the total duration of fixations on climbing holds divided by the total duration of fixations on the trial. This quantified the gaze behavior related to AOI as the participants searched for holds on the wall while climbing the new routes. These four measures were also used to better understand the relative visual entropy measure as its function is still under debate (for more detail, see the review of Shiferaw et al., 2019).

The relative visual entropy was calculated to assess the degree of uncertainty in the spatial pattern of participants' fixations during ascents (Shiferaw et al., 2019). Based on the classification of AOI, a sequence of visited AOI was created and the probability of looking at each AOI was computed (*p(i)*, *i* is an AOI). A transition matrix was created based on the sequence of visited AOI during the ascent and this matrix was converted into a probability matrix that gave the probability of transitioning from one AOI to another (*p(i,j)*, the probability of shifting from *i* to *j*) in each cell. Then, we computed the observed visual entropy with the following equation (Ellis & Stark, 1986):

$$H_{Observed} = -\sum_{i=1}^{n} p(i) \left[\sum_{j=1}^{n} p(i,j) \log_2 p(i,j) \right], i \neq j$$

This value was divided by the maximal entropy value to compute the relative visual entropy. The maximal entropy value referred to the equal probability that a participant would fixate one AOI or would shift from one AOI to another. Thus, it represents the complete randomness or unpredictability of the gaze path across AOI and it can be computed as $\log_2(N)$, with N the number of AOI available (Shiferaw et al., 2019). In the context of this study, the relative visual entropy was used to evaluate the degree of goal-directedness in the participants' gaze behaviors, with a high score indicating that the fixations were shifting from one hold to another unpredictably and a low score indicating that the fixations from hold to hold had gained in certainty.

All data treatments were computed on MATLAB R2014a software (version 8.3.0.532, The MathWorks Inc., Natick, MA, USA).

Statistical Analysis

Effects of Practice and Route Design on Motor Activity and Gaze Behaviors

A two-way repeated-measures ANOVA was applied to each dependent measure. The two factors were the three test sessions (practice) and the four climbing routes (route design). When necessary, the p values were corrected for possible deviation from sphericity using the Greenhouse-Geisser correction when the mean epsilon was lower than 0.75. Otherwise, the Hyun-Feld procedure was used. Planned simple contrast tests were used to assess the practice and transfer effects on all the dependent variables. The pretest and the Control route were used as references for the practice and route design factors, respectively. Thus, depending on the main factor and interaction effects revealed by the ANOVA, a maximum of 11 tests was performed (**Table 8**).

The effect size was determined with the partial eta squared (η_p^2) statistics, with $\eta_p^2 = .01$ representing a small effect, $\eta_p^2 = .06$ representing a medium effect, and $\eta_p^2 = .15$ representing a large effect. ANOVA and contrast tests were performed with SPSS software (version 21, SPSS Inc., IBM, Chicago, IL), with a level of statistical significance $p < .05$.

Relationship between Performance and Visual Entropy

The relationship between GIE and the relative visual entropy was examined using repeated measures correlation (rmcorr), with a level of statistical significance $p < .05$. The aim was to assess whether a complex hip trajectory was correlated with an uncertain gaze path and, conversely, whether a smooth hip trajectory was correlated with a more goal-directed gaze path. This statistical method controlled the effects of between-participant variance on the relationship between the two variables of interest (Bakdash & Marusich, 2017). The rmcorr was performed with the rmcorr R package (https://cran. r-project.org/web/packages/rmcorr/) on RStudio (version 1.1.383, RStudio Inc., Boston, MA, USA) with R programming language (version 3.5.1., R Development Core Team, Vienna, Austria).

Results

Performance

The three (practice) x four (route design) repeated measures ANOVA revealed a significant effect of practice on GIE [$F(1.08, 6.47) = 21.55$, $p = .003$, $\eta_p^2 = .78$, assumption of sphericity with Mauchly test: $\chi^2(2) = 9.65$; $p = .008$ so the Greenhouse-Geisser correction was applied with $\varepsilon = 0.54$]. The simple contrast tests (**Table 8**) revealed that the hip trajectory was less complex on the posttest (mean = 0.93, standard error = 0.05) and retention test (*M* = 1.00, *SE* = 0.07) compared to the pretest (*M* = 1.30, *SE* = 0.05).

The ANOVA confirmed that the route design also affected the complexity of the hip trajectory [$F(3,18) = 13.88$, $p < .001$, $\eta_p^2 = .70$]. According to the contrast tests, hip trajectory was less complex on the Control route (*M* = 0.89, *SE* = 0.03) than on the Distance (*M* = 1.12, *SE* = 0.08), Orientation (*M* = 1.12, *SE* = 0.06) and Shape (*M* = 1.18, *SE* = 0.03) routes.

The ANOVA also revealed an interaction between practice and route design [$F(6,36) = 7.71$, $p < .001$, $\eta_p^2 = .56$]. The contrast tests showed that between pretest and posttest, participants' GIE decreased more on Control (*M* = - 0.57, *SE* = 0.07) than on Shape (*M* = - 0.14, *SE* = 0.07) and Orientation (*M* = - 0.28, *SE* = 0.03), but it did not significantly differ from that on Distance (*M* = - 0.49, *SE* = 0.06). Similarly, the improvement in GIE between the pretest and retention tests was higher on Control (*M* = - 0.46, *SE* = 0.07) than on Shape (*M* = - 0.24, *SE* = 0.09) and Orientation (*M* = - 0.17, *SE* = 0.11), but it did not significantly differ from that on Distance (*M* = - 0.32, *SE* = 0.10). The values of GIE on each route and in each test session are displayed in **Figure 6**.

Some inter-participant differences can be highlighted. Participant 7 for example, showed little improvement and even an increase in GIE on the retention test compared to the pretest on the three transfer routes. This participant also showed the least improvement in her GIE on the posttest and retention test compared to the pretest on the Control route. On the other hand, participants 1, 2, 3, 4 and 5 improved their GIE scores in the posttest and retention test compared to the pretest on the three transfer routes. Moreover, participants 1 and 4 decreased their GIE on the Orientation route between the post- and retention tests, and similarly, participants 2, 3, 4 and 5 improved their GIE on the Shape route between the posttest and retention test. Participant 4 also demonstrated the largest improvement in GIE on the post- and retention tests compared to pretest on the Control route.

Table 8. Results of the contrasts tests.
Results of the contrasts tests on all the dependent variables for the factors Practice (Pretest vs. Posttest and Pretest vs. Retention test) and Route design (Control vs. Distance, Control vs. Shape and Control vs. Orientation) and the interaction of these two factors (Practice x Route design).

	Practice				Route design						Practice x Route design											
	Pre x Post		Pre x Re		Control x Dist.		Control x Shape		Control x Orient.		Pre-Post x Control-Dist.		Pre-Post x Control-Shape		Pre-Post x Control-Orient.		Pre-Re x Control-Dist.		Pre-Re x Control-Shape		Pre-Re x Control-Orient.	
	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2	$F_{1,6}$	η_p^2
Performance and Exploratory movements																						
GIE	85.88***	.94	13.03*	.69	18.88**	.76	132.49***	.96	36.16**	.86	0.82	.12	109.29***	.95	14.73**	.71	3.00	.33	36.42**	.86	19.99**	.77
NB of Expl.	54.00***	.90	67.50***	.92	/		/		/		/		/		/		/		/		/	
	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2	$F_{1,4}$	η_p^2
Gaze behaviors																						
NB of Fixations	18.49*	.82	8.86*	.69	52.68**	.93	180.89***	.98	73.11**	.95	/		/		/		/		/		/.	
Mean Dur. Fix.	/		/		/		/		/		/		/		/		/		/		/	
R. Dur. on AOI	/		/		/		/		/		/		/		/		/		/		/	
R. NB AOI	9.72*	.71	7.59	.66	19.23*	.83	59.26**	.94	56.20**	.93	0.24	.06	6.87	.63	1.39	.26	10.67*	.73	30.97**	.89	18.08*	.82
R. Visual Entropy	17.46*	.81	2.70	.40	15.27*	.79	33.55**	.89	33.53**	.90	/		/		/		/		/		/	

Notes. *p < .05; **p < .01; ***p < .001

/: The contrast test was not performed as the effect of the main factor was non-significant

Pre: Pretest; Post: Posttest; Re: Retention Test

Control: control route; Dist.: transfer route with increased distance between handholds; Shape: transfer route with new handhold shape; Orient.: transfer route with new handhold orientation

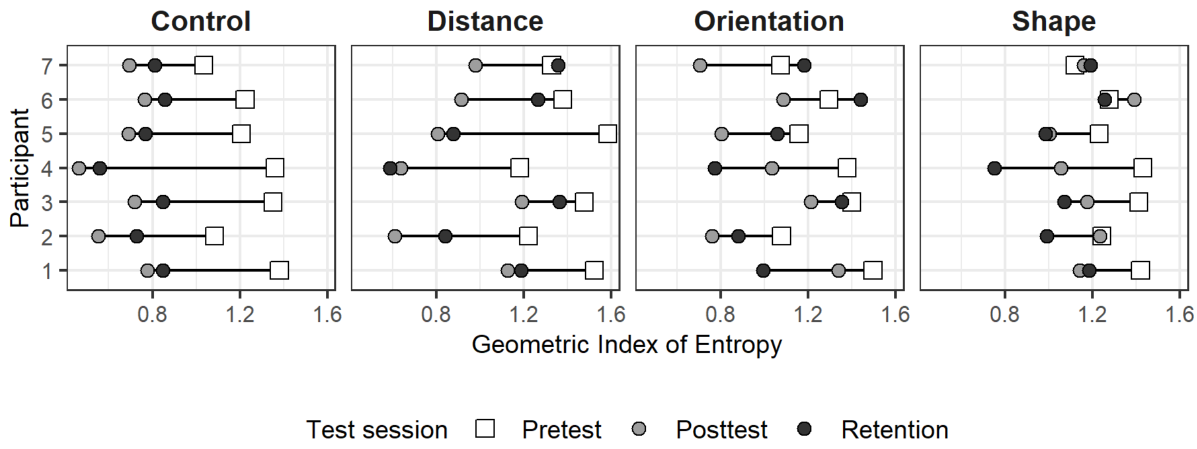

Figure 6. Participants' individual scores for the geometric index of entropy (GIE).
The shape of the points refers to the test session and each frame corresponds to one of the four routes climbed during the test sessions. The lines represent the participants' range of scores for each route. The lower the GIE score, the more fluent the climb of the route.

Number of Exploratory Hand Movements

The three (practice) x four (route design) repeated measures ANOVA revealed a significant effect of practice on the number of exploratory movements [$F(2,12) = 49.38$, $p < .001$, $\eta_p^2 = .89$]. The simple contrast tests (**Table 8**) revealed that the participants performed fewer exploratory movements on the posttest (M = 1.25, SE = 0.53) and retention test (M = 1.04, SE = 0.43) than on the pretest (M = 4.25, SE = 0.72). The ANOVA revealed no significant effect of the route design [$F(1.32,7.91) = 2.12$, $p = .186$, $\eta_p^2 = .26$, Mauchly test: $\chi^2(5) = 12.30$; $p = .034$ so the Greenhouse-Geisser correction was applied with ε = 0.44] or the practice x route design interaction [$F(2.70,16.2) = 2.43$, $p = .107$, $\eta_p^2 = .29$, Mauchly test: $\chi^2(20) = 43.09$; $p = .008$ so the Greenhouse-Geisser correction was applied with ε = 0.45]. The number of exploratory movements performed by the participants on the route handholds is presented in **Figure 7**.

Figure 7 showed that participant 1 performed more exploratory hand movements than the other participants in the three test sessions (at least one on all routes and in all tests). More specifically, this difference between participant 1 and the others was greatest on the Distance route. Participant 1 also always performed an exploratory movement on handhold 10 of the Control and Distance routes. Conversely, participants 4 and 5 were the only participants who did not use exploratory hand movements in the retention test on the four routes. Also, in the pretest, handholds 9, 10 and 11 of the Control and Distance routes appeared to invite the participants to perform more exploratory movements than the other handholds of the same routes.

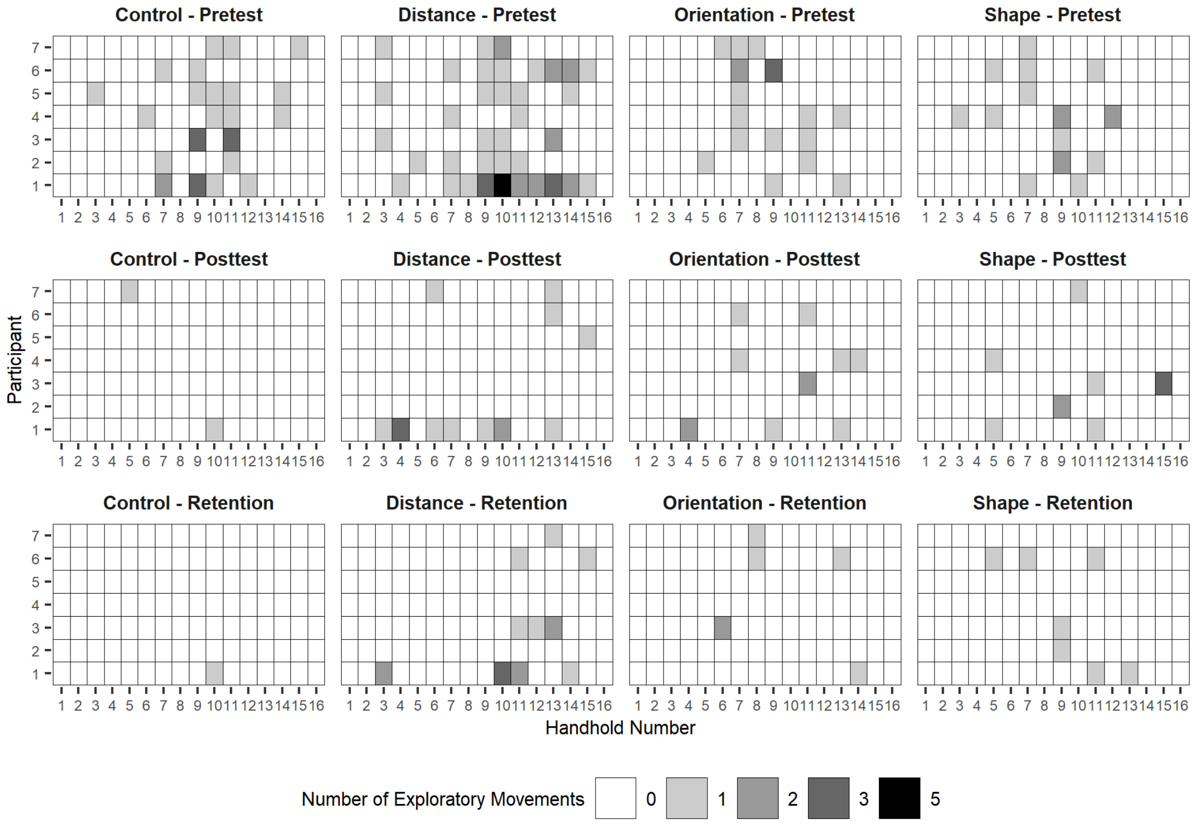

Figure 7. Number of exploratory movements performed by participants.
The heatmaps represent the participants' number of exploratory movements performed on the routes handholds. On each heatmap, lines correspond to participants and columns to handholds, and the darker the filling, the more the number of exploratory movements on the handholds. Each heatmap corresponds to the ascent of one route in one test session and they are organized to have one route per column and one test session per line.

Gaze Behaviors

Tracking Ratios

Due to poor tracking ratios, the gaze behaviors of two participants were not used in the statistical analysis. We therefore analyzed the gaze behavior of five participants. The tracking ratios for these five (M = 85.5% , SE = 2.06) were not significantly impacted by practice [$F(1.05,4.22) = 0.15$, $p = .730$, $\eta_p^2 = .04$, Mauchly test $\chi^2(2) = 6.80$, $p = .033$ so the Greenhouse-Geisser correction was applied with $\varepsilon = 0.53$], route design [$F(3,12) = 2.10$, $\eta_p^2 = .34$, $p = .154$], or the interaction of the two factors [$F(6,24) = 1.36$, $p = .271$, $\eta_p^2 = .25$] according to the repeated measures ANOVA.

Number of Fixations

The three (practice) x four (route design) repeated measures ANOVA revealed a significant effect of practice on the number of fixations [$F(2,8) = 11.16$, $p = .005$, $\eta_p^2 = .74$]. The simple contrast tests (**Table 8**) revealed that the number of fixations was lower on the posttest ($M = 85.30$, $SE = 4.53$) and retention test ($M = 91.60$, $SE = 7.04$) than the pretest ($M = 147.83$, $SE = 14.06$).

The ANOVA revealed that the route design also affected the number of fixations [$F(3,12) = 34.66$, $p < .001$, $\eta_p^2 = .90$]. According to the contrast tests, the number of fixations was lower on Control ($M = 74.83$, $SE = 4.95$) than on Distance ($M = 111.47$, $SE = 2.16$), Shape ($M = 129.07$, $SE = 5.27$) and Orientation ($M = 117.60$, $SE = 8.02$).

The ANOVA revealed no significant effect of the test x route interaction [$F(6,24) = 1.18$, $p = .351$, $\eta_p^2 = .23$]. Individuals' results are displayed in **Figure 8A**.

Mean Duration of Fixations

Practice [$F(1.05,4.20) = 4.79$, $p = .090$, $\eta_p^2 = .55$, Mauchly test $\chi^2(2) = 7.04$, $p = .030$ so the Greenhouse-Geisser correction was applied with $\varepsilon = 0.53$], route design [$F(3,12) = 0.64$, $p = .607$, $\eta_p^2 = .14$] and the interaction of the two factors [$F(6,24) = 0.93$, $p = .491$, $\eta_p^2 = .19$] had no significant effect on the participants' mean duration of fixations ($M = 252.12$, $SE = 8.15$), according to the ANOVA. Individuals' results are displayed in **Figure 8B**.

Relative Number of AOI Fixated

The three (test sessions) x four (routes) repeated measures ANOVA revealed a significant effect of practice on the number of fixated AOI [$F(2,8) = 6.95$, $p = .018$, $\eta_p^2 = .64$]. The simple contrast tests (**Table 8**) revealed that fewer AOI were fixated on the posttest ($M = 0.78$, $SE = 0.03$) than the pretest ($M = 0.89$, $SE = 0.01$), but the difference with the retention test did not significantly differ ($M = 0.78$, $SE = 0.04$).

The ANOVA confirmed that the route design also affected the number of fixated AOI [$F(3,12) = 20.33$, $p < .001$, $\eta_p^2 = .84$]. According to the contrast tests, the number of visited AOI was lower on Control ($M = 0.76$, $SE = 0.02$) than on Distance ($M = 0.82$, $SE = 0.03$), Shape ($M = 0.85$, $SE = 0.01$) and Orientation ($M = 0.84$, $SE = 0.02$).

The ANOVA also revealed a practice x route design interaction [$F(6,24) = 3.10$, $p = .022$, $\eta_p^2 = .44$]. The contrast tests showed that between pretest and posttest, the number of fixated AOI did not significantly differ between Control ($M = -0.18$, $SE = 0.05$), Distance ($M = -0.14$, $SE = 0.05$), Shape ($M = -0.04$, $SE = 0.03$), and Orientation ($M = -0.09$, $SE = 0.06$).

Conversely, between the pretest and retention test, the number of fixated AOI decreased significantly more on Control (*M* = - 0.21, *SE* = 0.04) than on Distance (*M* = - 0.07, *SE* = 0.04), Shape (*M* = - 0.09, *SE* = 0.05) and Orientation (*M* = - 0.08, *SE* = 0.05). Individuals' results are displayed in **Figure 8C**.

Relative Duration of Fixations on AOI

Practice [$F(2,8) = 0.93$, $p = .433$, $\eta_p^2 = .19$], route design [$F(3,12) = 2.14$, $p = .149$, $\eta_p^2 = .348$], and the interaction of the two factors [$F(6,24) = 0.37$, $p = .892$, $\eta_p^2 = .08$] had no significant effect on the participants' relative duration of fixations on AOI (*M* = 0.78 , *SE* = 0.03), according to the ANOVA. Individuals' results are displayed in **Figure 8D**.

Relative Visual Entropy

The three (practice) x four (route design) repeated measures ANOVA revealed a significant effect of practice on the relative visual entropy [$F(2,8) = 5.17$, $p = .036$, $\eta_p^2 = .56$]. The simple contrast tests (**Table 8**) revealed that the gaze path was more goal-directed on posttest (*M* = 0.29, *SE* = 0.02) compared to pretest (*M* = 0.37, *SE* = 0.02), but did not differ significantly on the retention test (*M* = 0.32, *SE* = 0.03).

The ANOVA revealed that the route design also affected the relative visual entropy [$F(3,12) = 18.09$, $p < .001$, $\eta_p^2 = .82$]. According to the contrast tests, the gaze path was more goal-directed on Control (*M* = 0.25, *SE* = 0.03) than on Distance (*M* = 0.33, *SE* = 0.03), Shape (*M* = 0.38, *SE* = 0.01) and Orientation (*M* = 0.34, *SE* = 0.02). The ANOVA did not reveal any significant effect of the test x route interaction [$F(6,24) = 1.38$, $p = .262$, $\eta_p^2 = .26$]. Individuals' results are displayed in **Figure 8E**.

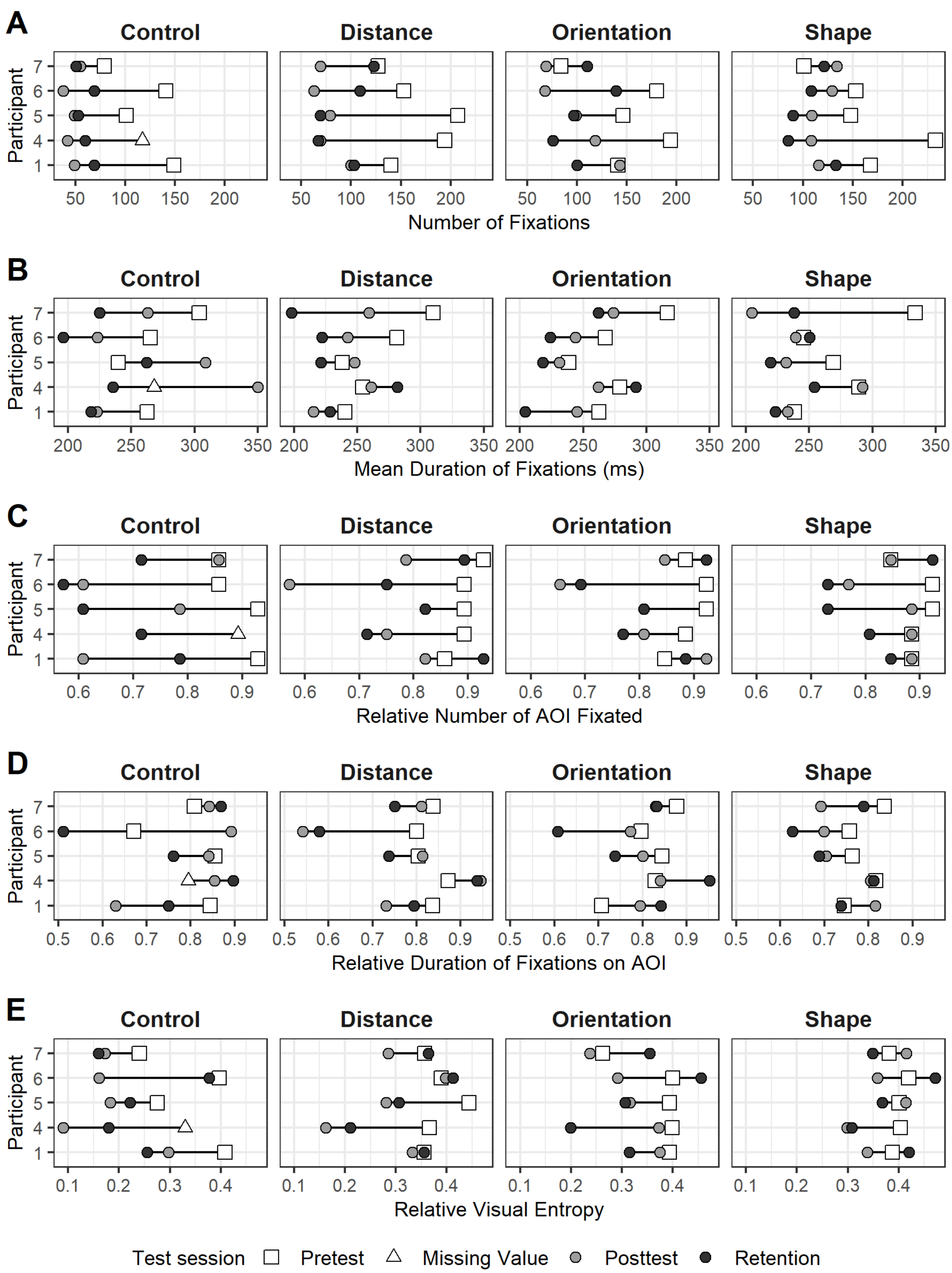

Figure 8. Participants' gaze behaviors.

Participants' individual values for the five dependent variables measured to assess gaze behaviors: (A) the number of fixations, (B) the mean duration of the fixations, (C) the relative number of AOI fixated, (D) the relative duration of fixations spent on AOI and (E) the relative visual entropy. The shape of the points refers to the test session. The values for participant 4 on the pretest for the Control route are replaced by the mean of the series.

Relationship between Performance and Visual Entropy

A repeated measures correlation was computed to assess the relationship between GIE and the relative visual entropy on the four routes (**Figure 9**). The results showed a positive correlation between the two variables on Control [r_{rm}(9) = .83; *95% CI*= [0.38, 0.96]; *p* = .001], Distance [r_{rm}(9) = .84; *95% CI*= [.41, .98]; *p* = .001], and Orientation [r_{rm}(9) = .84; *95% CI*= [.39, .96]; *p* = .001]. Thus, the more complex the participants' hip trajectory was on these routes, the more uncertain their gaze path was across AOI. Conversely, the smoother their hip trajectory was, the more goal-directed their gaze path was. However, this relation was not significant on Shape [r_{rm}(9) = .38; *95% CI*= [-.38, .83]; *p* = .254].

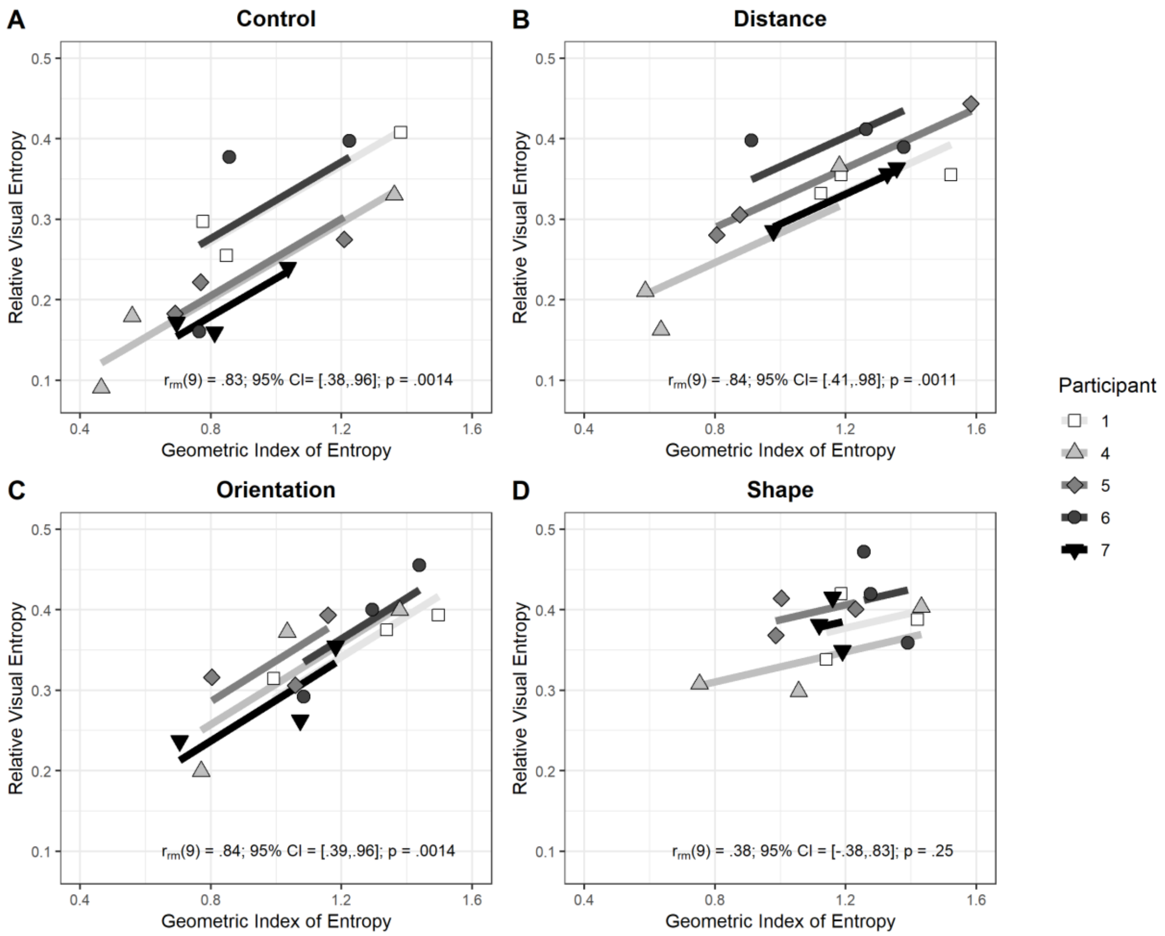

Figure 9. Relationship between the geometric index of entropy and relative visual entropy.
This figure displays the results of the repeated measures correlations (r_{rm}) with the boundaries of the 95% confidence interval (95% CI) and the *p* value. Each panel corresponds to one of the four routes performed during the test sessions: panel A refers the control route; B refers the route with and increased distance between handholds; panel C refers to the route with new handhold orientation; and panel D refers to the route with new a handhold shape. The points represent the participants' trials (N = 60) and the color identifies the participants. The lines represent the repeated measures correlation fit for each participant.

Discussion

The first aim of this study was to investigate the modifications of learners' exploratory activity during the acquisition of a perceptual-motor skill. The second aim was to determine to what extent the acquired perceptual-motor skill and the learners' exploratory activity were transferred to environments presenting novel properties. The results validated our hypothesis that the participants' exploratory activity would be more efficient with learning, as shown by (i) the decrease in the number of exploratory movements and fixations and (ii) the gain in goal-directedness of the gaze behavior on the learning route. Regarding the transfer of the route-finding skill, the results suggest that the participants transfer their skill to the route with an increased distance between handholds but not to the other two routes. Also, there were fewer exploratory movements following practice on the three transfer routes, which indicates that these learners relied more on exploration from a distance with learning. However, the number of fixations on the transfer routes was higher than on the learning route and a positive correlation between the entropy of the hip trajectory and the gaze path was observed on all routes except the route with a different handhold shape.

Less Exploratory Hand Movements with Learning

The results showed that the number of exploratory movements decreased with learning and that participants 4 and 5 were not even using these hand movements on the retention test for the four routes. This decrement in exploratory behaviors is in accordance with the literature. In climbing studies specifically, the number of exploratory movements either became lower in the learning protocols (Orth, Davids, & Seifert, 2018; Seifert et al., 2018) or increased in conditions of anxiety (Nieuwenhuys et al., 2008; Pijpers et al., 2005, 2006). Exploratory hand movements were also studied by confronting participants with tasks involving surprising ground surfaces (Joh & Adolph, 2006). This study suggested that exploratory movements were used to reveal haptic information about, for example, ground texture or ground density to avoid falling. Similarly, participants in the present study may have used exploratory hand movements initially to reveal information about handhold texture or saliences (i.e., bumps and hollows). However, no significant differences were observed between the number of exploratory movements on the Control route and the transfer routes following the learning sessions, which suggests that the information revealed by haptic exploration on the control route could be transferred to the transfer routes. Thus, haptic exploration had a prospective role, but the importance of this role seemed to decrease with experience. According to Kretch and Adolph's (2017) hypothesis of the ramping-up organization of exploratory actions, touching is one of the most engaging modes of exploration as it brings the individual into direct contact with an unknown surface. In the case of a climbing task, touching can inform on hold texture, shape, size, orientation, etc., in order to aid decisions on grasping and to apply friction forces. However, touching with a hand implies that the arm is no longer a support. Moreover, the task-goal (i.e., to climb the route as fluently as possible) may have prevented the participants from engaging in haptic exploration as it implied stops in the ascent. Thus, it is fair to assume that the decrease in the number of exploratory movements with practice was linked to the following: (i) over the course of practice, the climbers came to need the information revealed through these exploratory movements less and (ii) the exploratory movements were threatening to high performance or safety. Thus, in line with Kretch and Adolph's (2017) ramping-up hypothesis, exploration with learning may have been dominantly performed from a distance by the visual system.

Nevertheless, exploratory hand movements were still used following the leaning sessions and may have had other functions. **Figure 7** shows that these movements were unequally used by the participants. Participant 1 in particular used these movements remarkably more than any other participant in all the test sessions. These individual differences suggest that the participants may not have performed exploratory hand movements with the same purpose. Moreover, **Figure 7** suggests that the exploratory movements were used mainly on specific handholds (e.g., handholds 9, 10 and 11 on the Control and Distance routes) and that, even though the handholds were the same on the two routes, there seemed to be a tendency for fewer exploratory movements on the Control route than on the route with an increased distance between handholds, notably for participant 1. Thus, this mode of exploration may have been used by the participants (i) to better perceive whether the handhold was within reaching distance, (ii) to adjust their body position in order to prepare the next movement, or (iii) to try/adjust different grasping patterns in order to ensure the following movement. Exploratory movements may have been used at the beginning of the learning sessions to reveal information about handhold texture, but other functional roles would explain why this mode of exploration was still used after the sessions. However, these other functional roles need further and more specific investigations to be confirmed.

Less Gaze Activity with Learning

The results showed that after the learning sessions, the participants performed fewer fixations while they were climbing, but the duration of these fixations and the percentage of their viewing time spent fixating AOI (i.e., holds of the route) were not affected. These findings indicate that less gaze activity is needed with practice. Similar results were found in a climbing task with more experienced climbers: they reduced the number of fixations during ascents but the number of fixations per second (i.e., search rate) did not change with practice (Button et al., 2018). Thus, in accordance with the literature, the quantity of gaze activity seemed to decrease with learning as fewer fixations were performed to climb the routes.

Other variables may be useful for describing the state of visual exploration and the changes in the function of vision with learning. In their systematic review, Kredel et al. (2017) showed that the variables usually measured to investigate gaze behavior in performance contexts reveal (i) the source of information that performers rely on and (ii) the quantity of information taken from these sources. As illustrated by our results, these variables only reveal the changes in the quantity of gaze activity but not the qualitative changes induced by learning. Thus, in what follows, we discuss the use of the visual entropy measure to assess the learning-induced changes in the gaze path during the ascents.

Reorganized Gaze Behavior with Learning

As the relative duration spent on AOI did not change between pretest and posttest, it did not seem that the learners were searching for the holds on the wall and that as they learned they knew where to find the relevant information. Thus, it seems that with learning, the climbers did not merely change the quantity and sources of information to climb fluently. Instead, the results on visual entropy showed that the gaze path reorganized as it appeared to have become more goal-directed on the posttest compared to the pretest: the learners used vision first to look for handhold affordances by fixating them in an uncertain order, and then to guide their climbing actions by fixating the handholds in a more structured order. The results also showed that the number of fixated AOI (i.e., holds on the wall) decreased with learning, and if we refer to the formula used to compute the visual entropy (see Methods: Dependent Measures), this can affect visual entropy. Thus, the decrease in visual entropy can be attributed to (i) a more goal-directed gaze transition between climbing holds and (ii) a decrease in the number of fixated holds.

Although the quantity of gaze activity was lower on the retention test than on the pretest, this long-term effect was not observed for the reorganization of gaze behavior, even though the number of fixated holds was still lower during the retention test on the Control route than on the transfer routes. Here again, it seems that it was not sufficient to decrease the quantity of gaze activity to climb fluently, but that the learners also had to obtain information for affordances from the visual system to guide their actions. Indeed, the results on the retention test suggest that the learners were still not fixating some holds of the route (as in the posttest) but were shifting from one hold to another in a more uncertain way. Thus, it seems that the learners had more difficulty guiding their actions on the climbing route than they did on the posttest.

The repeated measures correlations calculated between GIE and visual entropy tended to confirm this insight: the more visual entropy decreased, the more the visual system seemed to be used to guide locomotion on the route. This relation between the two variables appeared to hold on all routes except the one with the new handhold shape. These results suggest that the new handholds of the Shape route disrupted the information-movement couplings developed on the Control route which prevented participants to transfer their exploratory activity and their route-finding skill to this new environment (see the following section for further discussion).

The reorganization of the gaze behavior can be discussed in the light of the recent hypothesis that exploratory activity differs according to the aim of exploration: exploration for orientation or exploration for action specification (van Andel et al., 2019). According to this hypothesis, exploration for orientation refers to the discovery of the different affordances that can be realized, whereas exploration for action specification refers to the selection of one affordance and the specification of its requirements in terms of movement control. The results on the reorganization in the participants' gaze behaviors on the posttests and the positive correlation between visual entropy and climbing fluency, seem to support this hypothesis on the learning timescale. Indeed, they suggest that exploration may have changed from a dominant aim to discover the affordances of the routes in the pretest, to exploration dominantly aimed at specifying the climbing movements in the posttest. However, further investigation is necessary to validate this assumption.

Limited Transfer of Route-finding Skill to the New Environments

The results validated the effect of practice on the learners' route-finding skill, which is a prerequisite to then assure the transfer of learning. GIE decreased significantly on the posttest and retention test in comparison to the pretest. This result indicates that the learners adopted a less complex and smoother hip trajectory to reach the top of the climbing route, thereby demonstrating more fluency in the chaining of their climbing movements (Orth, Davids, Chow, et al., 2018) and a higher degree of coherence in their perception-action coupling (Cordier, Mendés France, et al., 1994).

The transfer of route-finding skill to the climbing routes with local changes appeared limited. Although five of the seven participants showed improved climbing fluency on the three transfer routes in the post- and retention tests compared to the pretest, the results suggest that, as expected, the participants could effectively adapt their climbing actions when the new properties invited low-order behavioral changes (Distance route) but that they had more difficulties to adapt their climbing actions when the new properties induced high-order behavioral changes (Orientation route). Also, the results suggest that the change in handholds shape prevented transfer although the handholds could be used similarly to the original handholds (Shape route).

The lack of transfer to the Orientation route can be discussed at the light of the literature about transfer of calibration. In this literature, two opposite views exist. On one hand, a series of experiments by Rieser, Pick, Ashmead, and Garing (1995) proposed that the calibration of one coordination transfers to other coordinations that share the same function (e.g., calibration of forward walking transferred to side stepping). Similar findings were obtained in a more recent experiment that showed that calibration transfers from walking to crawling (Rob Withagen & Michaels, 2002). On the other hand, results in developmental studies showing that calibration was specific to the postural milestone, as children who were discovering new postures (e.g., learning to crawl) did not transfer their calibration from earlier postures (e.g., sitting to crawling) but had to discover the action boundaries enabled by the new posture (Adolph et al., 2008; Kretch & Adolph, 2013). Our results seem to fit the latter assumption that calibration is posture specific. Indeed, the high-order behavioral changes due to the change in handhold orientation may have disrupted the learners' chain of climbing actions by leading them into body postures that they had not previously experienced and that changed the actions they could perform with the following handholds.

As already observed, adapting to change in hold orientation requires lengthy practice as it forces the body to rotate from side to side like a pendulum and this body rolling must be controlled, whereas beginners naturally climb facing the wall (Seifert et al., 2015). To produce a positive transfer to the Orientation route, it is possible that the new body postures would have also needed to already be in the learners' motor repertoire prior to the transfer test.

Transfer of the route-finding skill was also negative on the Shape route. The new handholds were chosen to enable the same grasping pattern as the original handholds, but this pattern was hidden from the learners so that they would have to find the functional properties on the new handholds that were similar to those of the originals. Previous studies have shown that with expertise climbers develop a functional perception of the handholds as they perceive them in terms of the affordances that they allow rather than their structural properties (e.g., their dimensions, size, color, etc.) (Bläsing, Güldenpenning, Koester, & Schack, 2014; Boschker et al., 2002). According to our results, the learners did not transfer their functional perception from the Control route to the Shape route, so they may have used unreliable information to perceive affordances on the Control route, preventing a possible transfer of attunement (Smeeton, Huys, et al., 2013). Thus, the learners may have built their functional perception on the Control route on information that was too specific to the original handholds and that couldn't be retrieved with the new handholds of the Shape route, which conforms with the fundamental idea that affordances perception builds on highly specific individual-environment relationship (Gibson & Gibson, 1955). Interestingly, four participants improved their climbing fluency on this route between the posttest and retention test. This unusual result suggests that they may have benefited from the posttest trial to better perceive the affordances of the new handholds. This would also be congruent with the original proposition of Gibson and Gibson (1955) that perception of affordances builds on specific individual-environment relationships that develops with practice.

It should be also stressed that the protocol did not have the same effect on all the participants. Some inter-participant differences were observed, notably for the progression of participants 4 and 7 on the routes. Participant 7 showed the least improvement in climbing fluency, this fluency being even worse on the retention test than the pretest for the three transfer routes. In contrast, participant 4 showed the greatest improvement while learning on the Control route but also demonstrated considerable improvement on the three transfer routes, with a posttest result that improved even more on the retention test. Participant 4 may have greatly benefited from the learning sessions by developing skilled exploratory activity that gave him the ability to rapidly adapt to new features on the climbing routes (Adolph, 2008; Gibson, 1966).

Limitations and Perspectives

This study is original because it investigates gaze behaviors in a task representative of climbers' real activity (for a review of eye-tracking studies in sports, see Kredel, Vater, Klostermann, & Hossner, 2017). We proposed to use the relative visual entropy to assess the degree of goal-directedness from the spatial pattern of the gaze movements during the participants' ascents. This measure may be useful for informing qualitative changes in the spatial organization of the performers' gaze path in a rich and complex environment such as in this climbing task. However, the main limitation was the low number of participants whose gaze behavior could be used; this is a problem often encountered in the eye-tracking literature (Dicks, Button, et al., 2010; McGuckian, Cole, & Pepping, 2018; van Dijk & Bongers, 2014). Moreover, given the high variability in the participants' gaze behaviors (**Figure 8**), care is needed in drawing conclusions, and future research could focus more on the different strategies in gaze behaviors mobilized by performers (Dicks, Button, et al., 2017).

Also, the method used to assess the number and location of hand exploratory movements showed some limitations. Although numerous studies have used this method in climbing tasks, it is debatable whether a hand movement initially used with a primary informational purpose can reveal an appropriate fit between the climber and the handholds and enable the climber to turn exploratory movements into performatory ones. Thus, even though this method provides some insight into participants' attunement to handholds affordances, more precise methods could be developed to investigate climber-handholds interactions in order to achieve a finer-grained understanding of how climbers reveal and exploit information about handholds affordances. One example might be an analysis of their eye-hand coordination when they use or touch the handholds.

Conclusion

To summarize, this study helps to show how exploratory activity changes with the practice of a climbing task and to what extent this exploratory activity and the route-finding skill of learners could transfer to climbing routes with new handholds properties. Exploratory hand movements did not appear to be used solely to gather information as it seemed that some participants used them with additional functional purposes to climb the routes. The gaze activity appeared to decrease (fewer fixations during ascents) and reorganize with practice, which suggests that visual exploration was initially used by the learners to search the environment and then to guide their actions. However, although there was still less gaze activity on the retention test, its level of goal-directedness decreased; thus, the participants may have needed to search anew for the relevant information to guide their climbing movements. The individual performances in the tests indicate that some participants benefited more than others from the learning sessions to develop skilled exploratory activity. Performances at the group level suggest that the participants were able to transfer their route-finding skill to a new climbing route if (i) they had mastered the actions enabled by the new properties of the environment and (ii) they were attuned to the functional properties of the new environment.

Chapter 5: Effects of Practice Conditions on Behavioral Flexibility

Introduction

According to the dynamical systems approach, learning is the reorganization of the learner's behavioral repertoire (or intrinsic dynamics) in relation to task demands (Schöner et al., 1992; Zanone & Kelso, 1992). In complex tasks involving multiple degrees of freedom, experience appears to enable performers to demonstrate a rich behavioral repertoire that facilitates their adaptation to task demands. For example, in ice-climbing, expert performers were able to demonstrate a wide variety of interlimb coordination patterns to ascend an icefall, which enabled them to exploit the properties of their environment (Seifert, Wattebled, et al., 2014). Conversely, novices appeared stuck in certain interlimb coordination patterns and they forced their way by creating deep holes in the icefall (Seifert, Wattebled, et al., 2014). The development of a performer's behavioral repertoire should be possible through both exploring new behavioral solutions and exploiting existing behaviors (Komar et al., 2019; Schöner et al., 1992). Effective exploration during practice should result in individualized, adaptable behavioral solutions (Komar et al., 2019; Seifert, Komar, et al., 2016). This skilled adaptability results from an appropriate tradeoff between the stabilization of solutions (resulting in persistent transformations in the behavioral repertoire) and the flexibility of these solutions, which enables their use in different variations of the set of constraints (Seifert, Button, & Davids, 2013).

Previous studies using a bimanual coordination task paradigm showed that, depending on the relation between the learner's initial behavioral repertoire and the task demand, the learning route can take the form of a shift or bifurcation (Kostrubiec, Tallet, & Zanone, 2006; Kostrubiec et al., 2012; Zanone & Kelso, 1992, 1997; Zanone, Kostrubiec, Albaret, & Temprado, 2010). Using a scanning procedure to assess the range of stable coordination patterns in learners' repertoires, these studies showed that when the repertoire cooperated with the coordination pattern to be acquired, a coordination pattern already present in the repertoire shifted toward the trained coordination so that the overall shape of the repertoire did not qualitatively change. Conversely, when the coordination to be acquired competed with the repertoire, a qualitative improvement in the repertoire was observed as the acquired coordination pattern was added to the preexisting stable patterns. This last learning route is called bifurcation as the learning dynamics show a phase transition with the sudden appearance of the new coordination pattern (Zanone & Kelso, 1992). However, studies that have used more complex perceptual-motor tasks have also pointed out that participants can show poor learning (i.e., weak performance improvement and no modification in the behavioral repertoire) due to a lack of effective exploration (Chow et al., 2008; Orth, Davids, Chow, et al., 2018). A possible explanation offered in one of these studies was that these participants showed a limited behavioral repertoire prior to practice, which therefore restrained the movement solutions and the potential for exploration in the learning environment (Orth, Davids, Chow, et al., 2018). A solution to encourage the exploration of new behaviors and avoid having learners stay in the comfort zone of their initial repertoire is to provide external perturbations by varying the task parameters with unstructured or structured variations (Ranganathan & Newell, 2013). Unstructured variations consist in changing multiple task parameters simultaneously to force the exploration of new behavioral solutions (e.g., Schöllhorn et al., 2006), whereas structured variations are designed to guide exploration with variations in only one or few parameters such that learning is generalized to only the varied parameters (e.g., Huet et al., 2011). In sum, variations during practice encourage learners to explore task redundancy by searching in different areas of the perceptual-motor workspace and discovering the many-to-one relation between the behavioral solutions and the performance outcomes (Newell, McDonald, & Kugler, 1991; Pacheco, Lafe, & Newell, 2019).

Although encouraging exploration appears beneficial to learning, exploiting the discovered behavioral solutions also matters in reshaping learners' behavioral repertoires in the long term. Over-exploration, or randomly navigating in the perceptual-motor workspace during practice, can be detrimental to learning when it does not respect the individual's learning dynamics, as this would result in not stabilizing the newly discovered behavioral solutions in the learner's repertoire (Hossner et al., 2016; Komar et al., 2019). This issue may be solved by giving learners some control over when to vary the task parameters. For example, Liu et al. (2012) showed that learners given the possibility of regulating task difficulty had more success in the task during practice and on posttest compared to groups of learners who practiced with regular increments in difficulty. Another study showed that learners benefited from having control over their practice schedule while practicing three variations of a three keystroke task, as they showed better performance outcomes on transfer tests in comparison to a yoked group (Wu & Magill, 2011). The benefits of self-controlled learning were attributed to the possibility for participants to adapt their learning protocols in line with their search for task solutions and their current skill level (Y.-T. Liu et al., 2012; Sanli, Patterson, Bray, & Lee, 2013). When they were unsuccessful, they could thus change the task and maintain motivation or, conversely, they could keep on practicing the task while working to improve their performance (Y.-T. Liu et al., 2012). The effect of self-controlled learning on learners' behavioral flexibility has not yet been investigated, however, although some studies suggest that individualizing learners' rate of exploration during practice may be effective (Y.-T. Liu et al., 2012; Sanli et al., 2013).

The aim of this study was to use a scanning procedure to determine whether giving learners the possibility of choosing when to confront task variations during a learning protocol would result in greater flexibility in their motor repertoire in comparison to giving an imposed schedule of task variations or a constant practice condition.

We thus designed a climbing task that would encourage learners to search for ways to fluently chain their climbing movements. A skilled chain of movements was adapted to both the layout of the wall holds and the participants' action capabilities in such a way that that they would limit the movements of their center of mass and the time spent immobile (Cordier, Mendés France, et al., 1994; Orth, Davids, Chow, et al., 2018). To facilitate this chaining of action, the learners needed to master two hand coordination patterns: alternating between hands in consecutive climbing movements (hand alternation) or repeating two or more consecutive movements with the same hand (hand repetition). Thus, a subgoal of this study was to examine the preferences of novice climbers regarding these two coordination patterns. We expected that hand alternations would predominate in the initial repertoires of most participants as this coordination pattern is naturally used in simpler climbing tasks (e.g., ladder climbing, Hammer & Schmalz, 1992), whereas we expected a lower proportion of participants would initially use hand repetitions.

The scanning procedure consisted in climbing three routes under three instruction conditions. These conditions were neutral, congruent or incongruent with the route design, enabling us to assess to what extent the participants could flexibly use the two-hand coordination pattern in the different hold layouts. The interaction between these two task constraints was designed to affect their climbing behavior: the route design by restricting the possible movement solutions and the instruction by directing their intentions (Newell, 1986; Pol et al., 2020). In this regard, we expected that on pretest, the task constraints would conflict with the participants' repertoires in conditions where hand repetition was expected or where the hold layouts competed with hand alternation. Then, we hypothesized different learning outcomes for our three learning groups. First, the learners in the constant practice condition would demonstrate low flexibility with the two coordination patterns in posttest and retention due to the lack of exploration of the perceptual-motor workspace during practice, whereas the two groups with task variations would show more ease in adapting the two patterns to the different sets of task constraints. Thus, the main differences between the groups would be observed in incongruent route-instruction conditions. Second, the self-controlled group would show less interindividual variability in the learning outcomes in comparison to the group experiencing imposed task variations, as all the learners in this latter group might not have sufficiently stabilized the new behavioral solutions in their repertoires. Thus, we expected that a larger proportion of participants in the self-controlled group would show improved behavioral flexibility in comparison to the group with imposed task variations.

Method

Participants

Twenty-four participants volunteered to take part in this study, but two dropped out in the first session. For the remaining twenty-two participants (8 females and 14 males), the mean age was 20.6 years (SD = 1.1), mean height 172.4 cm (SD = 7.0), mean weight 66.4 kg (SD = 10.8), and mean arm span 171.7 cm (SD = 8.3). They were undergraduate students at the sports faculty of the University of Rouen Normandy. Their skill level was in the lower grade group according to the International Rock Climbing Research Association scale (Draper et al., 2015) as they had no or very little climbing experience. The protocol followed the Declaration of Helsinki. The protocol was explained to the participants and they gave their written informed consent before starting the experiment. They were distributed into three learning groups: n = 7 in the constant practice group (CPG, i.e., practice on a single climbing route), n = 7 in the imposed variability group (IVG, i.e., practice on the control route and on imposed variants) and n = 8 in the self-controlled variability group (SVG, i.e., practice on the control route and on chosen variants).

Learning Design

Participants in each group were prompted to climb the routes as fluently as possible, i.e., avoiding stops and saccades. They were also prompted to use all the handholds of the climbing route in a bottom-up order and, if two handholds were at the same height, they had to use the two handholds but they could choose the order.

The participants performed three test sessions and ten learning sessions. The test sessions were designed as scanning procedures and were common to all groups, whereas the learning sessions differed between groups. The first session was a pretest followed by the learning sessions and a posttest. A retention test was organized five weeks later. All the sessions took place on an artificial climbing wall. Each session lasted about one hour and started with a 10-minute warm-up on easy boulder routes in the bouldering area of the climbing gym.

Test Sessions.

To test the flexibility of the hand alternation and hand repetition coordination patterns, we designed the test sessions as a scanning procedure. Scanning procedures were originally developed for bimanual coordination tasks to measure to what extent an individual would be able to perform and maintain the whole range of possible relative-phases between hands (Zanone & Kelso, 1992, 1997). In this way, the researchers could observe which coordination patterns were stable for each individual. In multi-articular tasks such as climbing, a scanning procedure was also designed to assess whether participants would be able to climb facing the wall and/or climb side to the wall (Orth, Davids, Chow, et al., 2018). In this scanning procedure, the participants had to climb a route under three conditions: a free condition, with instructions to climb side to the wall as much as possible, and with instructions to climb facing the wall as much as possible. Similar to this scanning procedure, we manipulated the instructions given to the participants: the first condition was a free condition for observing the participants' spontaneous behavior, and in the other two conditions they were instructed to perform one of the two coordination patterns (i.e., hand alternation or hand repetition) as much as possible on the climbing route. Moreover, as climbing studies have shown that the manipulation of the environmental properties of a climbing route can encourage climbers to perform one coordination pattern over another (Orth, Davids, & Seifert, 2018; Seifert et al., 2015), we also manipulated the hold layouts on the wall to design three climbing routes: two that would facilitate one coordination pattern over the other and one that would enable both patterns on each movement. These three routes were respectively called the alternation route, the repetition route and the neutral route (**Appendix A**, **Figure 37**).

The routes were all designed with 13 handholds including the starting handhold, and we thus focused on the 11 movements between the first handhold after the starting handhold and the last handhold. Based on the instruction given and the layout of the handholds, we assumed that (i) on the neutral route the climbers would perform hand alternation and hand repetition equally well on each movement (**Figure 10**), (ii) on the alternation route the climbers would perform hand alternations on all the transitions between handholds (**Figure 11**), and (iii) on the repetition route the climbers would switch between hand alternation and hand repetition (6 hand repetitions and 5 hand alternations) (**Figure 12**). In order to test the stability of the two coordination patterns, the instructions were also manipulated during the test sessions. In the first three climbs of these sessions, the participants climbed the three routes without additional instructions so that we could see their spontaneous hand coordination on the routes. In the following six climbs, they had to redo the same ascents but trying to use repetition (for 3 climbs) or alternation (for 3 climbs) as much as they could. Thus, in these six climbs, the route-instruction conditions could be congruent or incongruent.

Learning Sessions

The ten learning sessions were performed over five weeks following the pretest. Participants had two sessions per week with a minimum of one day between two sessions. During sessions 1 and 10, the participants had seven climbs to perform. On sessions 2 to 9, they had nine climbs. The first climb in session 1 and the last climb in session 10 were performed on a transfer route. The other 84 climbs differed between groups as illustrated in **Table 9**.

The CPG performed the 84 trials on the control route. The IVG climbed the control route three times per session followed by one or two blocks of three climbs on a variant route. The participants in this group had a new variant route in each session; thus, they climbed a total of nine variants and had six trials per variant. The SVG differed from the IVG on the schedule of the variant routes. In this group, the participants had the opportunity to choose whether they wanted to climb the same routes in the next session or they wanted to climb a new route. For example, at the end of session 2, the experimenter asked the participants if they wanted to continue their practice on variant 1 in the next session or if they wanted to practice on a new route (variant 3). If the participants always chose to have a new route, their variants schedule would be the same as for the participants in the IVG. Pictures of all the climbing routes are available in **Appendix A**.

Table 9. Contents of the learning sessions for the three groups.

Learning Session	Constant Practice	Imposed Variability	Self-Controlled Variability
Session 1	1xTR | 6xCR	1xTR | 3xCR | 3xV1	1xTR | 3xCR | 3xV1
Session 2	9xCR	3xCR | 3xV1 | 3xV2	3xCR | 3xV1 | 3xV2
Session 3	9xCR	3xCR | 3xV2 | 3xV3	3xCR | 3xV? | 3xV?
Session 4	9xCR	3xCR | 3xV3 | 3xV4	3xCR | 3xV? | 3xV?
Session 5	9xCR	3xCR | 3xV4 | 3xV5	3xCR | 3xV? | 3xV?
Session 6	9xCR	3xCR | 3xV5 | 3xV6	3xCR | 3xV? | 3xV?
Session 7	9xCR	3xCR | 3xV6 | 3xV7	3xCR | 3xV? | 3xV?
Session 8	9xCR	3xCR | 3xV7 | 3xV8	3xCR | 3xV? | 3xV?
Session 9	9xCR	3xCR | 3xV8 | 3xV9	3xCR | 3xV? | 3xV?
Session 10	6xCR | 1xTR	3xCR | 3xV9 | 1xTR	3xCR | 3xV? | 1xTR

Note: On the first and last sessions, the participants climbed a transfer route (TR). The participants in the Constant Practice group climbed a control route (CR) 6 to 9 times per session. The participants in the Imposed variability group climbed the control route 3 times in all sessions and they climbed 9 variant routes (V1 to V9) across the learning protocol. The participants in the Self-controlled variability group started the first two sessions as the Imposed variability group but at the end of the second session, they were asked if they wanted to train on a new route instead of V1 or if they wanted to continue training on it. This was asked at the end of all the sessions until the ninth, thus the participants in this group had individualized variants scheduled (V?).

Data Collection

The participants wore a light and an inertial measurement unit (HIKOB FOX®, Villeurbanne, France) on the back of their harnesses on all the trials. This sensor recorded the signals from an accelerometer, a gyroscope and a magnetometer at 100Hz. Ascents were filmed at 29.97 fps on 1920x1080 pixel frames with a GoPro Hero 5® camera (GoPro Inc., San Mateo, CA, USA) covering the entire wall. The harness light was video tracked on Kinovea© software (version 0.8.25, Boston, MA, USA) to obtain the climbers' coordinates of hip trajectory projection on the 2D wall. The camera lens distortion was compensated by importing the intrinsic parameters of the camera and the video perspective was corrected using a manually set grid-based calibration on this software.

Using the videos of the climbs, two trained coders annotated all the participants' hand and foot movements. They had to code (i) the moving limb and (ii) the hold that was reached by the moving limb. The coding of the videos was performed on BORIS© software (version 7.7.3, University of Torino, Italy) (Friard & Gamba, 2016). Intercoder reliability was assessed on nine trials. The coders agreed on 97.4% of the events (n = 195).

Data Treatment

Improving climbing fluency means better chaining of climbing movements in both space and time. Changes in climbing fluency can show different dynamics according to the measured dimension (Orth, Davids, Chow, et al., 2018; Rochat et al., 2020). Thus, to differentiate the potential changes in climbing fluency along a spatial, temporal or global dimension, we measured three indicators of movement fluency. These indicators were computed on each climb using the coordinates of the hip and the data from the inertial measurement unit: (i) the percentage of climbing time spent immobile (Orth, Davids, Chow, et al., 2018), (ii) the geometric index of entropy (Cordier, Mendés France, et al., 1994), and (iii) the jerk of hip orientation (Seifert, Orth, et al., 2014). The percentage of climbing time spent immobile is based on a hip velocity threshold (20cm.s^{-1}) and reveals the climber's temporal fluency. The geometric index of entropy reflects the complexity of the hip trajectory and informs about the climber's spatial fluency. The jerk of hip rotation corresponds to the quantity of saccadic movements in the hip motion and served as a global measure of the climber's fluency.

The coded events were used to measure the number of hand alternations and the number of hand repetitions on each ascent. A hand alternation was counted when the climber used his/her two hands one after the other, whereas a hand repetition was using the same hand for two consecutive movements. Moreover, we used the coded events to measure the number of ipsilateral hand movements (e.g., the right hand used a handhold on the right side of the route) and the number of contralateral hand movements (e.g., the right hand used a handhold on the left side of the route).

Statistical Analysis

All statistical analyses were performed in R (R Core Team, 2019).

To identify the participants' initial behavioral tendencies, we performed a descriptive analysis of the hand movements during the pretest. We examined the proportion of (i) hand alternations and (ii) hand repetitions performed with each hand in each climbing condition. We also examined the proportion of ipsilateral hand movements and contralateral hand movements performed on each handhold.

Then, we analyzed the effect of the three learning conditions on the participants' behavioral flexibility. In this aim, a k-means cluster analysis was performed to discretize the participants' different behavioral patterns during the test sessions. This analysis was performed with the kmeans function. The three fluency indicators and the number of hand alternations and repetitions were used in the cluster analysis after being centered and scaled so that the obtained behavioral patterns would be differentiated by the participants' hand coordination and/or aspects of their climbing fluency. The optimal number of clusters was identified with the maximum value of the Calinski and Harabasz criterion (Caliński & Harabasz, 1974). This criterion is a penalized ratio of the between-cluster dispersion and the within-cluster dispersion of the trials. It was computed for two to 15 clusters with the vegan package and the cascadeKM function (Oksanen et al., 2019). A descriptive analysis of the clusters was performed to assess the discriminant parameters. The effects of the practice condition (Group), test session (Session), given instruction (Instruction) and climbing route (Route) on the repartition of each cluster were evaluated with generalized linear mixed models (GLMM, Bolker et al., 2009) for binary data, with the cluster appearance as the dependent variable. All variables (Group, Session, Instruction and Route) and their possible interactions were included as fixed effects and the participant ID as a random intercept in the initial model. Then, we used an iterative model selection by eliminating the fixed effects one by one (drop1 function), and we selected the best model with the Akaike information criterion (AIC) and the likelihood ratio test with the Anova function. It was assumed that the model with the lowest AIC value would be the one with the lowest complexity but would best explain the variance of the data. The main effects in the final model were tested with the Wald chi-square test, which was computed with the Anova function in the car package (Fox & Weisberg, 2018). All the models were fitted with Laplace approximation and the glmer function of the lme4 package (Bates, Mächler, Bolker, & Walker, 2015). The post-hoc multiple comparisons of the least square means were performed on selected contrast tests with the Bonferroni correction applied to the p-values. Least squares means were computed with the lsmeans package (Lenth, 2016). In all tests, alpha was set at .05.

Results

What Are the Initially Preferred Hand Coordination Patterns Performed by Novice Climbers?

The 198 climbs performed by the 22 participants during the pre-test session were included in the descriptive analysis of the hand coordination patterns.

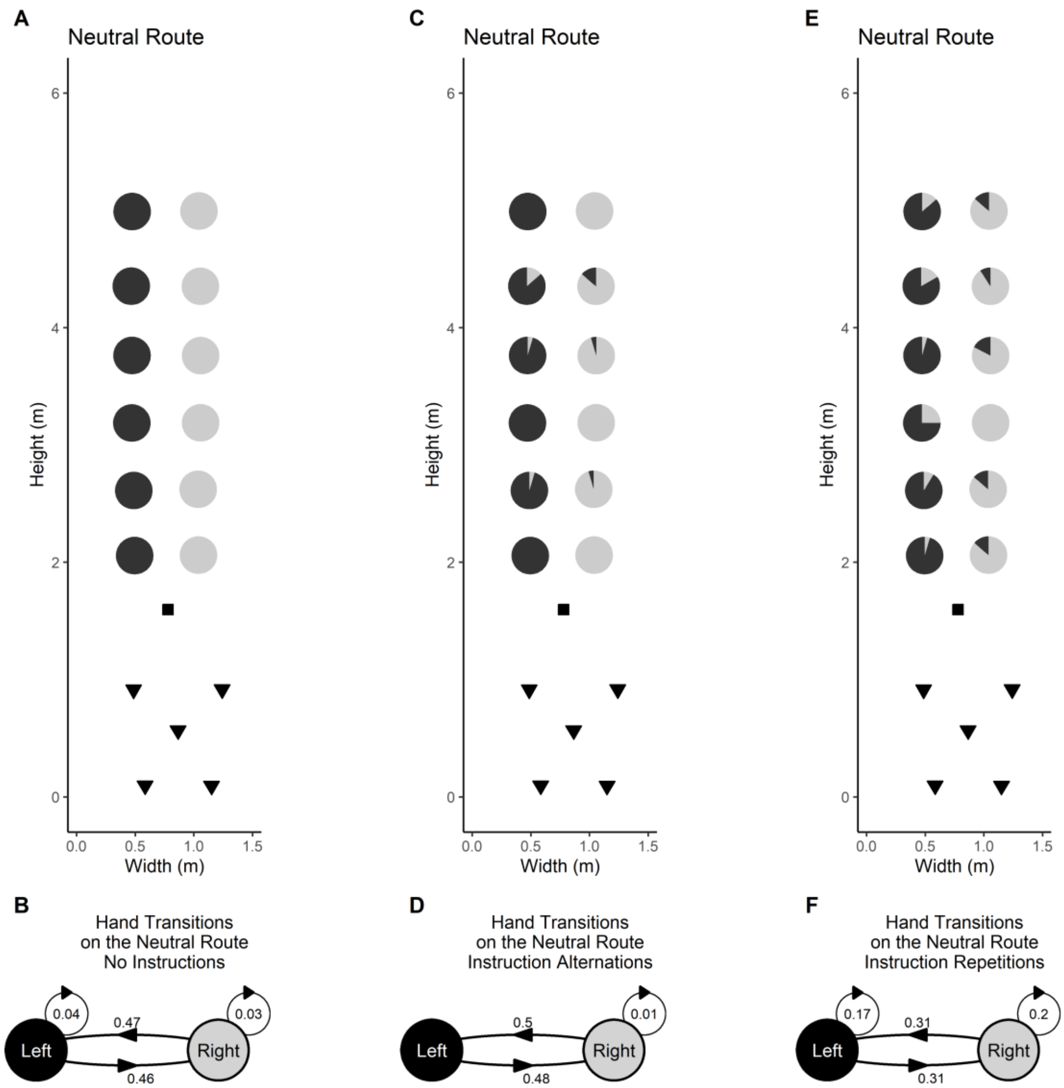

Figure 10. Hand coordination on the neutral route.
Hand coordination on the neutral route in the condition with no additional instruction (panels A and B), with the instruction to perform hand alternations (panels C and D), and with the instruction to perform hand repetitions (panels E and F). Panels A, C and E represent the neutral route with triangles for the footholds, a square for the starting handhold and pie charts for the handholds. The pie charts display the proportion of right hand (gray) or left hand (black) use of the respective handhold. In panels B, D and F, the black circle represents the left hand and the gray circle the right hand; the arrows going from one circle to the other and the associated values above show the proportion of hand alternations and the arrows staying on the same circles and the associated values show the proportion of hand repetitions.

The neutral route (**Figure 10**) was designed with handholds at the same level to enable both hand alternation and repetition without needing to use contralateral hand movements when reaching a higher handhold. Thus, participants could perform a maximum of 45% hand repetitions without using contralateral hand movements. In the condition with no additional instruction given, the participants never used contralateral hand movements and performed 7% hand repetitions and 93% hand alternations. When the instruction was to perform alternations, contralateral hand movements appeared in a range of proportions of 5% to 14% according to the handhold, with hand alternations performed for 98% of the movements and hand repetitions for the remaining 2%. With the instruction to perform repetitions, participants showed 38% hand repetitions and 62% hand alternations, which is close to the maximum of expected hand repetitions without crossing hands; however, the use of contralateral hand movements ranged between 0% and 25%, depending on the handhold.

On the alternation route (**Figure 11**), the participants performed hand alternations with ipsilateral movements exclusively (100% of hand movements) in the conditions with no additional instruction and the instruction to perform alternations. When the instruction was to perform repetitions, the participants performed hand alternations (61%) and hand repetitions (39%), which required them to use contralateral hand movements for 4% to 54% of the hand movements, depending on the handhold.

On the repetition route (**Figure 12**), the participants performed 33% hand repetitions and 67% hand alternations in the condition with no additional instruction, with 4% to 44% contralateral hand movements, depending on the handhold. The proportion of hand repetitions increased when participants were instructed to perform them (51%), which lowered the number of contralateral hand movements (range depending on handhold from 0% to 18%) in comparison to the condition with no additional instruction. Conversely, the proportion of hand repetitions decreased when the instruction was to perform alternations (9%), which increased the use of contralateral hand movements (range from 5% to 78%), with more than 50% on six of the 12 handholds.

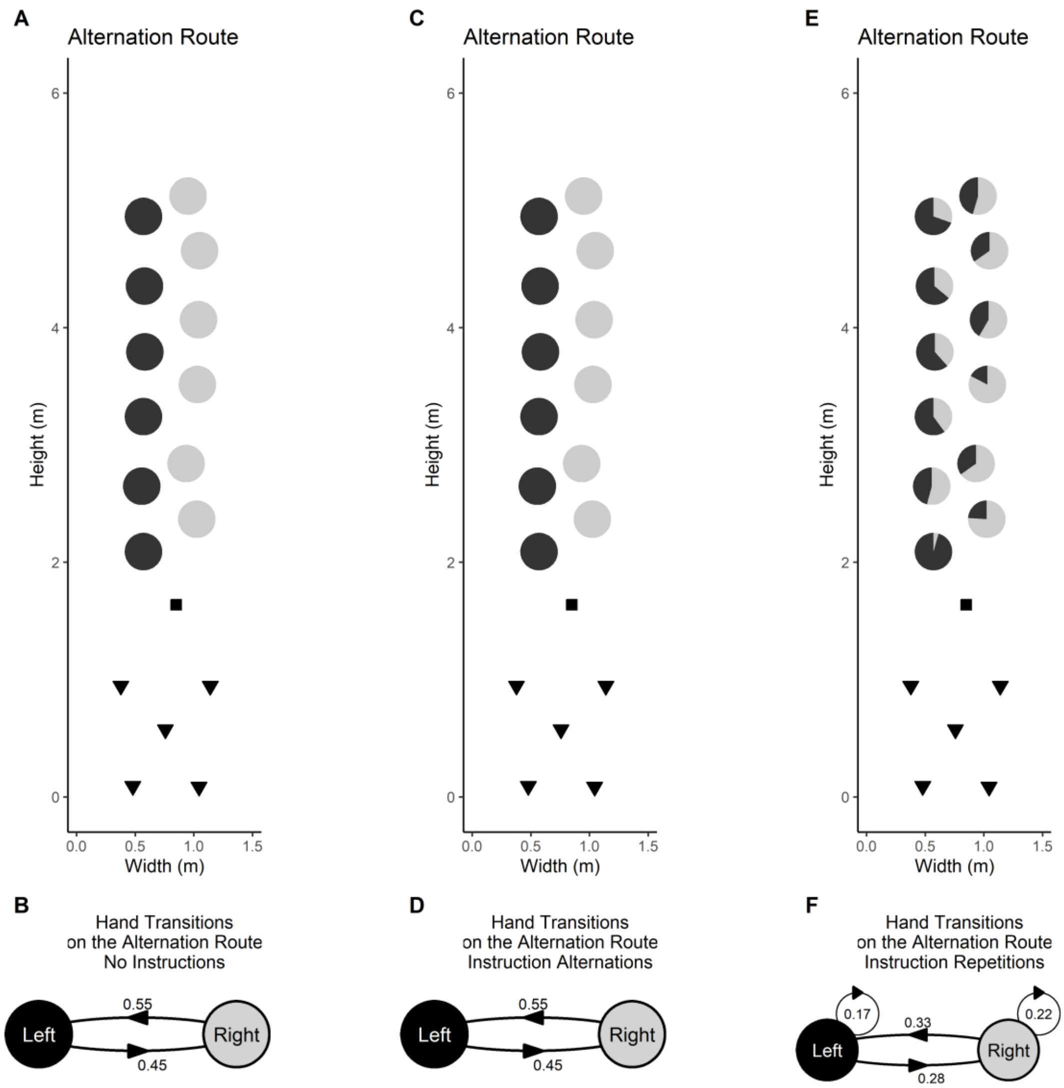

Figure 11. Hand coordination on the alternation route
Hand coordination on the alternation route in the condition with no additional instruction (panels A and B), with the instruction to perform hand alternations (panels C and D), and with the instruction to perform hand repetitions (panels E and F). Panels A, C and E represent the neutral route with triangles for the footholds, a square for the starting handhold and pie charts for the handholds. The pie charts display the proportion of right hand (gray) or left hand (black) use of the respective handholds. In panels B, D and F, the black circle represents the left hand and the gray circle the right hand; the arrows going from one circle to the other and the associated values above show the proportion of hand alternations and the arrows staying on the same circles and the associated values show the proportion of hand repetitions.

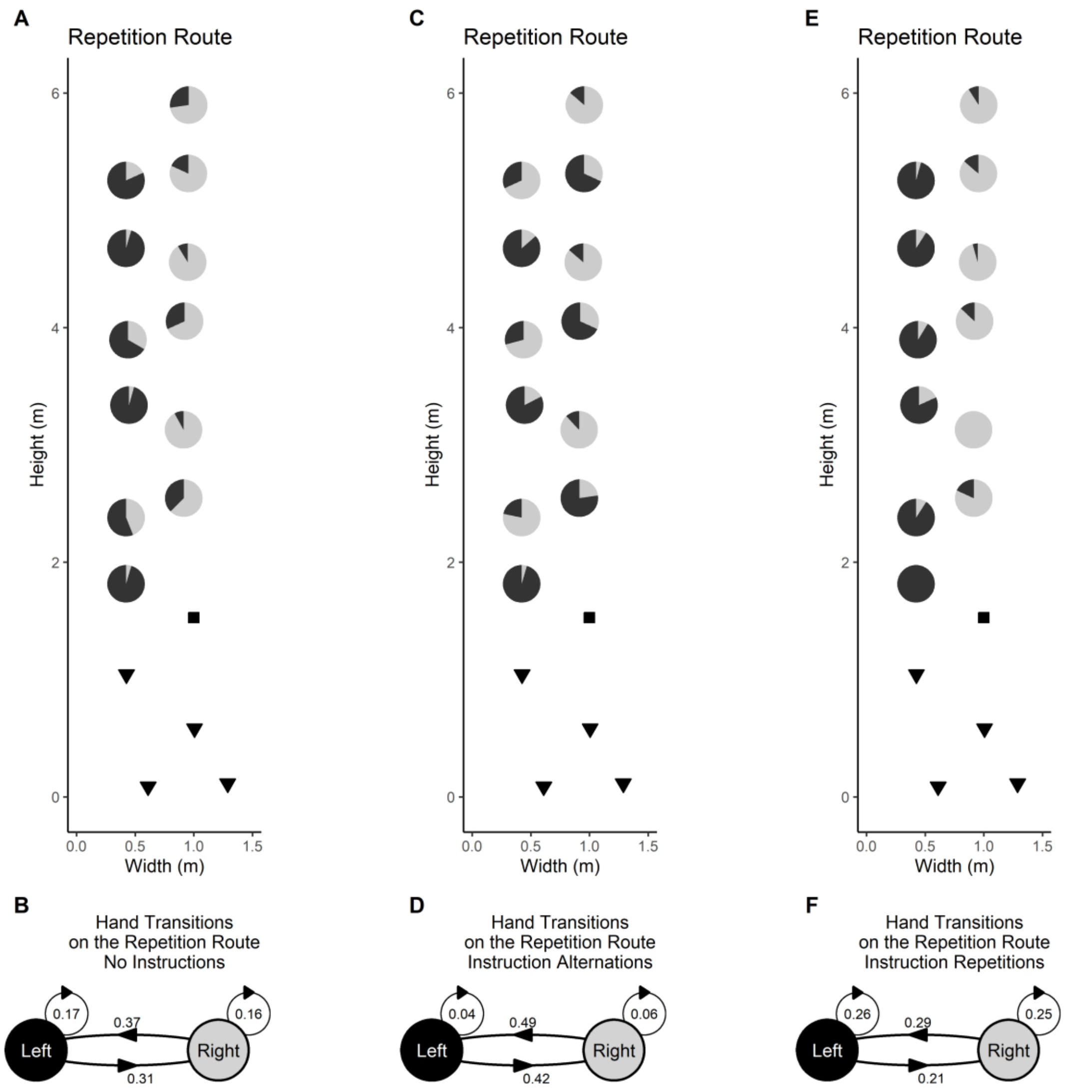

Figure 12. Hand coordination on the repetition route.
Hand coordination on the repetition route in the condition with no additional instruction (panels A and B), with the instruction to perform hand alternations (panels C and D), and with the instruction to perform hand repetitions (panels E and F). Panels A, C and E represent the neutral route with triangles for the footholds, a square for the starting handhold, and pie charts for the handholds. The pie charts display the proportion of right hand (gray) or left hand (black) use of the respective handholds. In panels B, D and F, the black circle represents the left hand and the gray circle the right hand; the arrows going from one circle to the other and the associated values above show the proportion of hand alternations and the arrows staying on the same circles and the associated values show the proportion of hand repetitions.

What Are the Effects of the Learning Conditions on Behavioral Flexibility?

Schedules of the Task Variations for the Self-Controlled Variability Group

At the end of sessions 2 to 9, the participants of the SVG chose between one to four times to continue their practice on the same route rather than climbing a new route. Thus, none of the participants in the SVG followed the same schedule of variant routes as the participants in the IVG, and two of the participants of the SVG climbed the nine variant routes during the learning sessions (they chose to keep variant 8 on session 10).

Cluster Analysis

The final sample used in the cluster analysis was 564 trials as some trials were excluded due to missing data.

The largest Calinski Harabasz criterion (CH) value was obtained for a model with five clusters (CH = [310.4, 368.1, 351.9, **379.1**, 364.6, 343.0, 327.5, 317.4, 311.8, 307.3, 301.2, 294.4, 289.7, 283.7]). Thus, a k-means cluster analysis was performed to partition the trials into five groups. The distribution of the clusters in the Group, Sessions, Route and Instruction conditions is displayed on **Figure 13**.

The means and standard deviations of the five variables included in the cluster analysis were computed for each cluster and are displayed in **Table 10**. Results showed that the trials in cluster 1 and cluster 4 presented almost exclusively hand alternations but these two clusters differed in the fluency indicators, with more fluent climbs in cluster 4 compared to cluster 1. Clusters 3 and 5 showed mixes between hand alternations and hand repetitions but they differed in the fluency indicators, with more fluent climbs in cluster 5 than in cluster 3. Finally, cluster 2 was composed of very few trials with very poor climbing fluency in comparison to the other clusters, and the climbs were performed with a tendency to use mostly hand alternations and a few hand repetitions.

Table 10. Descriptive statistics of the clusters.
Mean and standard deviation (±) of the variables for the corresponding cluster.

Variable	Cluster 1 (n = 115)	Cluster 2 (n = 12)	Cluster 3 (n = 79)	Cluster 4 (n = 197)	Cluster 5 (n = 161)
Number of Alternations	10.52 ±0.81	9.75 ±2.14	5.90 ±1.79	10.58 ±0.81	5.52 ±1.08
Number of Repetitions	0.58 ±1.00	3.33 ±2.31	5.85 ±1.73	0.42 ±0.82	5.62 ±1.04
Immobility Rate (%)	33.84 ±7.70	46.68 ±8.77	36.58 ±8.49	16.80 ±5.90	20.38 ±7.17
Geometric Index of Entropy ($\log_2$)	0.86 ±0.12	1.32 ±0.21	1.09 ±0.17	0.62 ±0.12	0.65 ±0.14
Jerk of Hip Rotation (ln)	13.61 ±0.71	16.33 ±0.40	14.51 ±0.98	11.56 ±0.94	12.27 ±0.97

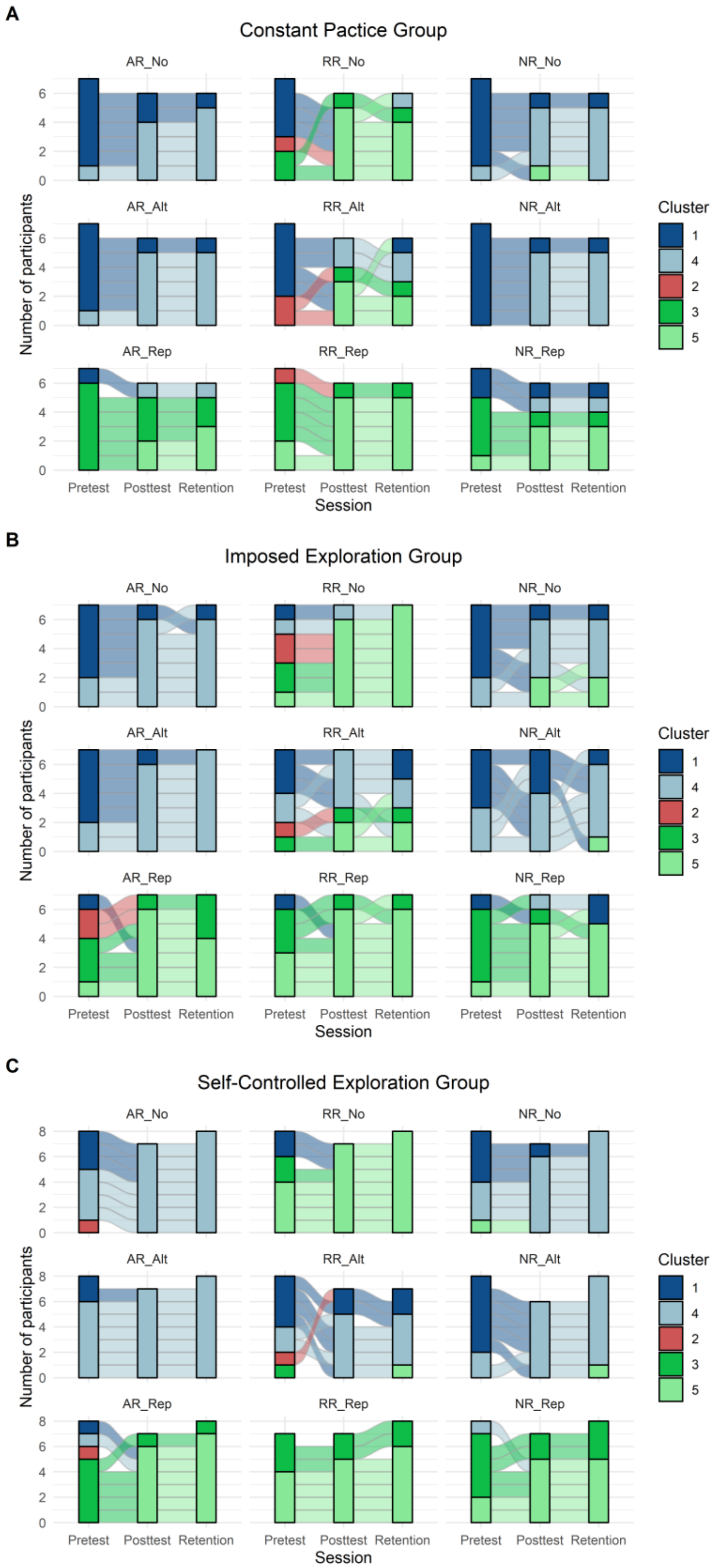

Figure 13. Distribution of the clusters among conditions.

Cluster distribution for the Constant Practice Group (A), Imposed Variability Group (B) and Self-controlled Group (C). Each panel is divided into nine frames distributed in three columns and three rows. Each column corresponds to one route design (i.e., AR, RR and NR refer to the alternation route, repetition route and neutral route, respectively) and each row to a given instruction (i.e., No, Alt and Rep refer to no additional instruction, hand alternation and hand repetition, respectively). In the frames, each bar displays one of the test sessions (i.e., pretest, posttest or retention test). The height of the bar signifies the number of participants. The colors of the bars correspond to the clusters of trials.

Repartition of the Clusters across Group, Session, Route and Instruction Conditions

Cluster 1. The final GLMM applied to cluster 1 [*AIC* = 398.1] included the fixed effects Group, Session, Route and Instruction and the interaction between Route and Instruction and between Group and Route. The analysis of deviance revealed a significant effect of the factors Group [$X^2(2) = 6.52$, $p = .038$], Session [X^2 (2) = 83.29, $p < 0.001$], Route [X^2 (2) = 9.09, $p = .011$], and Instruction [X^2 (2) = 38.09, $p < 0.001$] and a significant effect of the interaction between Route and Instruction [$X^2(4) = 9.57$, $p = .048$] and a non-significant effect of the interaction between Route and Group [$X^2(4) = 8.07$, $p = .089$].

Post-hoc analysis revealed that cluster 1 was more present in the CPG (29%) than in the SVG (13%). No significant differences appeared with the IVG (21%). This cluster was more present in pretest (43%) than posttest (8%) or retention test (8%). For clarity, only the significant results of post-hoc analysis of the interaction between Route and Instruction will be presented here, with the other results available in the **Supplementary Information** (**Table 11**) When no additional instruction was given, cluster 1 was more present in the neutral route (32%) and the alternation route (30%) than the repetition route (11%). When the instruction was to perform alternations or repetitions, no significant differences appeared between routes. On the neutral route, cluster 1 was more present in the conditions with no additional instruction or with the instruction to perform alternations (32% and 37%, respectively) than when the instruction was to perform repetitions (11%). Similarly, on the alternation route, there were more trials from cluster 1 in the conditions with no additional instruction or with the instruction to perform alternations (30% and 25%, respectively) than when the instruction was to perform repetitions (5%). On the repetition route, there were more trials from cluster 1 when the instruction was to perform alternations (31%) than when it was to perform repetitions (2%) or when there was no additional instruction (11%).

Cluster 2. No model could be developed for cluster 2 due to the rare appearance of this cluster (n = 12). This cluster was only observed on pretest and was not present in the other sessions. It was also present in the three groups. Half the trials from this cluster appeared in the two incongruent conditions (i.e., on the alternation route with the instruction to perform repetitions and on the repetition route with the instruction to perform alternations) and 67% appeared on the repetition route.

Cluster 3. The final GLMM built with cluster 3 [*AIC* = 314.6] included only the main fixed effects Group, Session, Route and Instruction. The removal of the interaction between

Route and Instruction affected the model [*AIC* = 289.4], showing that the integration of this interaction would better explain the data. It had to be removed as the model with this interaction did not show convergence due to the poor number of trials belonging to this cluster in multiple Route x Instruction conditions. As this interaction appeared to explain the distribution of the cluster, a descriptive analysis was performed at this level. The analysis of deviance of the final model revealed a significant effect of the factors Session [X^2 (2) = 28.24, p < 0.001] and Instruction [X^2(2) = 72.57, p < .001], whereas the factors Group [X^2(2) = 0.499, p = .779] and Route [X^2(2) = 4.59, p = .101] were not significant.

The post-hoc tests (**Supplementary Information**, **Table 12**) showed that the trials belonging to cluster 3 were more present on pretest (23%) than on posttest (9%) or retention test (9%). They were also more present when the instruction was to perform repetitions (35%) than when it was to perform alternations (3%) or when there was no additional instruction (4%).

The descriptive analysis showed that this cluster was never observed on the neutral route or the alternation route when no additional instruction was given or when the instruction was to perform alternations. However, with these instructions but on the repetition route, 13% and 10% of the trials, respectively, belonged to cluster 3. When the instruction was to perform repetitions, the route design did not seem to affect the frequency of the appearance of this cluster (35% on the neutral route, 29% on the repetition route and 40% on the alternation route).

These results showed that cluster 3 disappeared with practice. The instruction to perform repetitions facilitated the observation of this cluster. In the other instruction conditions, cluster 3 appeared only on the repetition route.

Cluster 4. The final GLMM applied to cluster 4 [*AIC* = 386.7] included the fixed effects Group, Session, Route and Instruction and the interaction between Group and Session, Session and Route, and Session and Instruction. The interactions between Route and Instruction were removed due to non-convergence, although the model including it had a lower AIC (*AIC* = 378.4). Thus, a descriptive analysis at the level of this interaction was performed. The analysis of deviance for the final model showed a significant effect of the factors Session [X^2(2) = 36.71, p < .001], Route [X^2(2) = 56.86, p < .001] and Instruction [X^2(2) = 76.96, p < .001], and the interactions between Group and Session [X^2(4) = 12.27, p = .015], Session and Route [$X^2(4) = 12.93$, $p = .012$], and Session and Instruction [$X^2(4) = 14.70$, $p = .005$], whereas the factor Group [$X^2(2) = 2.18$, $p = .336$] was not significant.

The post-hoc tests (**Supplementary Information**, **Table 13**) revealed that the trials from cluster 4 were less present on pretest (17%) than on posttest (44%) or retention test (45%). The tests performed at the level of the interaction between Group and Session revealed that this effect was confirmed only for the CPG, whereas it was not significant for the other two groups, although **Figure 13** shows that in the conditions concerned by hand alternations (the alternation route with no additional instruction and the three routes with the instruction to perform alternations), the proportion of trials belonging to this cluster increased on posttest and retention test compared to pretest.

Cluster 4 was less present when trials were performed on the repetition route (14%) than on the neutral route (41%) or the alternation route (49%). It was also significantly more present in trials on the alternation route than on the neutral route. The interaction between Session and Route showed that the practice effect was not significant on the repetition route but was significant on the other two routes. It also showed that on pretest, cluster 4 was less present on the repetition route (8%) than the alternation route (26%). On posttest and retention test, this cluster was less present on the repetition route than on the other two routes.

Regarding the effect of the instructions, cluster 4 was less observed when the instruction was to perform repetitions (4%) than when no additional instruction was given (44%) or the instruction was to perform alternations (57%). It was also significantly less present when no additional instruction was given than when the instruction was to perform alternations. The interaction between Session and Instruction revealed a significant effect of practice in the condition with no additional instruction and the condition with the instruction to perform alternations; however, it did not appear when the instruction was to perform repetitions. The proportion of trials from cluster 4 differed between the condition with the instruction to perform alternations and the condition with no additional instruction only on posttest (with 75% and 53%, respectively), whereas these two conditions showed higher proportions of cluster 4 in the three test sessions compared to the condition with the instruction to perform repetitions.

The descriptive analysis of the interaction between Route and Instruction showed that there were very few trials from cluster 4 on the three routes when the instruction was to perform repetitions and on the repetition route in the condition with no additional instruction (range from 0% to 6%). When the instruction was to perform alternations on the repetition route, the proportion was about a third of the trials (37%), whereas in the other route and instruction conditions, more than 50% of the trials belonged to cluster 4 (range from 59% to 75%).

Cluster 5. The final GLMM applied to cluster 5 [AIC = 380.6] included only the main fixed effects Group, Session, Route and Instruction, although the removal of the interaction between Route and Instruction affected the AIC score [AIC = 345.2]. The model was not convergent with this interaction due to the rare appearance of this cluster in some of the Route x Instruction conditions, and a descriptive analysis was thus performed at this interaction level. The analysis of deviance of the final model showed a significant effect of the factors Session [$X^2(2) = 59.91$, $p < .001$], Route [$X^2(2) = 73.75$, $p < .001$] and Instruction [$X^2(2) = 90.73$, $p < .001$], whereas Group was not significant [$X^2(2) = 1.76$, $p = .416$].

The post-hoc tests (**Supplementary Information**, **Table 14**) revealed that the trials were less present in pretest (10%) than posttest (39%) or retention test (38%). They were also more present when climbs were performed on the repetition route (50%) than on the neutral route (20%) or the alternation route (15%). Cluster 5 was also more present when the instruction was to perform repetitions (54%) than when no additional instruction was given (24%) or when the instruction was to perform alternations (6%). It was also more present when no additional instruction was given than when the instruction was to perform alternations.

Regarding the Route x Instruction conditions, this cluster never appeared on the alternation route when no additional instruction was given or when the instruction was to perform alternations, but the proportion was high when the instruction was to perform repetitions (46%). Similarly, the proportion was very low on the neutral route when no additional instruction was given and when the instruction was to perform alternations (10% and 3%, respectively), but high when the instruction was to perform repetitions (48%). On the repetition route, the proportion was high when no additional instruction was given and when the instruction was to perform repetitions (67% and 68%. respectively) and lower when the instruction was to perform alternations (16%).

Discussion

The aim of this paper was to determine whether giving learners the possibility to choose when to be confronted with task variations would result in a higher proportion of these learners showing greater behavioral flexibility in comparison to those following an imposed schedule of task variations and those in a constant practice condition. A subgoal of this study was to examine the initial behavioral tendencies of novice climbers during a scanning procedure regarding their ability to perform two coordination patterns. Results showed that the manipulation of the handhold layouts and instructions successfully encouraged the use of hand alternation or the switching between hand alternation and hand repetition. The participants showed strong initial tendencies (i) to prefer hand alternation over hand repetition even when the constraints enabled both and (ii) to avoid contralateral hand movements during the ascents. However, in the incongruent route-instruction conditions and in the repetition conditions, they were encouraged to demonstrate to what extent they could escape from these tendencies and adapt to the constraints. With learning, participants from the three groups globally showed more use of coordination patterns involving hand repetitions, and they more often showed fluent coordination patterns. No clear differences in the learning outcomes appeared between the CPG and the IVG, but the SVG stood out from the other two groups on posttest as all the participants in this group demonstrated coordination patterns that fit the route design in the conditions with no or congruent instructions and that fit the instructions in incongruent conditions. These results suggest that an individualized rate of exploration in a self-controlled practice condition may have helped the learners to improve their behavioral flexibility in our climbing task, whereas imposing variability did not seem more beneficial than constant practice. Regarding these results, we discuss (i) the effects of the interacting constraints on the participants' behavior, (ii) the initial behavioral tendencies shown by the participants on pretest, (iii) the difficulty for some participants in the CPG and IVG to escape their initial behavioral tendencies, and (iv) the potential reasons for the SVG to show more homogeneous learning outcomes than the IVG.

Effects of the Interacting Constraints on the Participants' Climbing Behavior

The test sessions were designed as a scanning procedure with two task constraints manipulated simultaneously: route design and instructions. We expected that the interaction between these two task constraints would affect the participants' climbing behavior: route design by restricting the possible movement solutions and instructions by directing the participants' intentions (Newell, 1986; Pol et al., 2020). We expected that this design would reveal both (i) the participants' spontaneous behavior in the condition without instruction and (ii) their behavioral flexibility in conditions with instruction congruent or incongruent with the route design.

When no instructions were given, the participants were keener to perform hand alternations on the alternation route and hand repetitions on the repetition route, as illustrated by the repartition of the clusters related to hand alternation (clusters 1 and 4) and hand repetition (clusters 3 and 5) on these two routes. On the neutral route, however, the participants preferred to perform the hand alternation pattern (**Figure 13**), although this route was designed to enable both patterns. This observation confirmed our expectation that participants would demonstrate, at least on pretest, a tendency to prefer hand alternations over hand repetitions (this point is discussed at length in section 4.2.). Thus, the results showed that the route design effectively constrained the climbing behaviors, although it did not prescribe them, as the behaviors instead appeared to have emerged from the interaction between the participants' repertoires and the task constraints, as observed in previous studies (e.g., Seifert et al., 2015; Zanone & Kelso, 1992).

Then, when the instruction about a coordination pattern was given, the participants were able to sharply change their climbing behavior. Notably, the proportion of clusters related to hand repetition (clusters 3 and 5) was null or very low on the alternation and neutral routes when the instruction was to perform hand alternation. But when the instruction changed and promoted hand repetition, the proportion of these clusters became largely dominant (**Figure 13**). The opposite effect was also observed on the repetition route. Thus, the instructions directed the participants' intentions during the climbs as their climbing behavior changed according to the instructions between congruent and incongruent route-instruction conditions. These results indicate that task constraints can be used to amplify and/or reduce behavioral information (Pol et al., 2020; Schöner et al., 1992), notably here as the additional instructions were able to prompt the participants to perform one coordination pattern over another even though the climbing route did not change.

Participants Showed Initial Tendencies to Prefer Hand Alternation and to Avoid Contralateral Hand Movements

As expected, the results showed that the participants initially demonstrated strong tendencies to perform hand alternations. The tendency for hand alternation was striking on the alternation route and the neutral route, although the neutral route was designed so that both coordination patterns could be performed. Moreover, the results also showed that on pretest, the clusters related to hand repetition (clusters 3 and 5) appeared for half of the participants on the repetition route when no additional instruction was given, whereas the other half of the participants performed a majority of hand alternations, even if the route design encouraged another hand coordination. However, the results also showed that the participants could escape this tendency for hand alternation when they had to perform under the repetition instruction, thus demonstrating behavioral flexibility even on pretest. It was also interesting to see the emergence of cluster 2 on pretest, which, regarding the corresponding fluency scores and behavioral measures, indicated the novice climbing behaviors that maladaptively tried to cope with the task constraints. The distribution of this cluster again suggests that some participants initially had difficulties in climbing the repetition route and performing hand repetitions on the alternation route. One reason for this may have been that, if the participants tried to use only hand alternations on the repetition routes, the task would require crossing the hands or at least having one hand above the other. **Figure 10, 11 and 12** show that the participants seemed to prefer performing ipsilateral movements (in the horizontal or diagonal direction) over contralateral movements (grasping a handhold above another already grasped or crossing hands horizontally or diagonally). This tendency to avoid contralateral movements was also observed in the spontaneous behavior of beginners in ice-climbing (Seifert, Wattebled, et al., 2014). These beginners displayed poor variability in the angle formed by their ice-tools, which were almost exclusively placed horizontally or diagonally (Seifert, Wattebled, et al., 2014). In contrast, expert climbers were able to use a large range of the possible interlimb angles, such as diagonal, horizontal, vertical or crossed limb position, to exploit the environmental constraints (e.g., to hook existing holes in the ice). This tendency of novices to avoid contralateral movements can be explained by the demand in terms of postural regulation and force equilibrium during such movements (Quaine et al., 2017). By placing the two hands vertically, climbers can resist the rotation toward the side of the two hands or they can use this rotation and climb with the whole body side to the wall (Seifert et al., 2015). However, the first strategy would be detrimental for chaining movement fluently and the second is characteristic of skilled climbing behavior (Seifert et al., 2015). Similarly, crossing the hands requires the regulation of body balance while moving the hands differently than when performing ipsilateral movements and can be facilitated by using whole-body motion. Thus, in order to develop behavioral flexibility, the participants had to discover how to use hand alternations and hand repetitions fluently in various postures during practice.

Constant Practice and Imposed Variability Lead to Similar Learning Outcomes: Stabilization of Hand Repetitions but Difficulties with Contralateral Movements for some Participants

We assumed that successful learning conditions in the test sessions would entail the participants learning to exploit the hold layout on the climbing wall and, in the incongruent conditions, demonstrating flexibility by using hand alternations or hand repetitions on an unfavorable route design. The results did not show any significant differences between the CPG and the IVG, and the individual learning outcomes were quite similar on posttest and retention test, as shown by the global distribution of the clusters for these two groups (**Figure 13**). The two groups appeared to have stabilized hand repetitions and to be able to more fluently chain their movements when using them, as shown by the increase in the proportion of cluster 5. They also seemed able to chain their movements more fluently when performing hand alternations, as shown by the increase in cluster 4 (**Figure 13**). These results suggest that in a complex pluri-articular task like climbing, increasing the movement variability with task variations may not always be more productive in terms of learning than letting learners explore through the variability inherent to them as complex neurobiological system (Chow, Davids, Button, Rein, & Hristovski, 2009). Indeed, the design of the control route on which the CPG had already practiced gave them the opportunity to explore hand alternations and hand repetitions in many postures. Thus, it seems that when the learning environment already provides a landscape rich in possible movement variations, additional task variations may not be necessary or beneficial to learning.

Nevertheless, some participants in these two groups appeared to be unable to perform hand alternations on the repetition route when the instruction was to do so, and some continued to perform hand alternations on the neutral route and the alternation route when the instruction was to perform repetitions. These observations suggest that some of the participants failed to escape from the initial tendency to avoid contralateral hand movements and were unable to discover new behavioral solutions. This failure was also observed in another study on climbing that indicated that a learner's inherent variability may not be sufficient when the task demand is competing with the initial behavioral repertoire (Orth, Davids, Chow, et al., 2018). This lack of change in behavior with practice was also observed in a task of kicking a football to target, with the participants following a protocol with task variations in each learning session: kicking the ball to four different targets (the same four targets were used in each learning session) (Chow et al., 2008). One participant in this study almost never changed the coordination pattern used to kick the ball during practice, demonstrating a lack of search of the perceptual-motor workspace (Chow et al., 2008; Y.-T. Liu, Mayer-Kress, & Newell, 2006). For the IVG, the imposed task variations aimed to increase this search behavior. Nevertheless, in a case-study investigating the dynamics of a learner's experience following a similar protocol (although here the learner was interviewed after each session), the participant experienced the need to cross hands as making an error in the chaining of climbing movements (Rochat et al., 2020), even though contralateral hand movements are not necessarily detrimental to climbing fluency. Indeed, crossing hands can be useful to regulate balance differently than the balance regulation with ipsilateral movements. Thus, participants may deliberately refrain from searching some areas of the perceptual-motor workspace even if the learning conditions are pushing them to do so.

Self-Controlled Schedule of Task Variations Leads to More Homogeneous Learning Outcomes among Participants

Interestingly, all the participants of the SVG showed the expected hand coordination patterns on posttest. This homogeneous group effect suggests that the individualized schedules of task variations helped stabilize the hand repetitions and the use of contralateral hand movements. In contrast, the imposed schedule of task variations and the constant practice condition may not have been adequate for some of them, who seemed to have searched the perceptual-motor workspace less efficiently than those in the SVG. Previous results showed that self-controlled schedules facilitated the transfer and retention of learning (Wu & Magill, 2011) and the acquisition of new coordination (Y.-T. Liu et al., 2012). Thus, the observations of the current study agree with and extend earlier results showing that a self-controlled schedule of task variations appears to facilitate the development of behavioral flexibility by being more respectful of the individual learning dynamics.

Moreover, all the participants in the SVG chose at least once to maintain the same variant route on more than two learning sessions, suggesting that they judged the minimum of six trials insufficient for exploring the possible movements on a given variant route in order to find an optimal chain of movement. Indeed, they might have encountered a local difficulty on the route (known as the crux point in climbing) and wanted to overcome it by finding an appropriate movement solution. Thus, by choosing to practice more on a variant route, they were able to progressively search the perceptual-motor workspace for a behavioral solution to resolve this crux point, rather than engaging abruptly with a new climbing route. This would be in line with the observations of Liu et al. (2012), who showed that the participants in a self-controlled practice group regulated the task difficulty according to their skill level, whereas participants following a schedule with a regular increase in task difficulty could not cope with this schedule, which lowered their success rate during practice especially in the later trials. As in the current study, the participants who did not manage to perform hand alternation on the repetition route were probably less skilled. The IVG participants may have used protective strategies, such as the one described in the case-study of Rochat et al. (2020), for coping with crux points in variants. In the SVG, however, they could choose to give themselves more trials to accumulate practice and potentially reach the critical instant of discovering an adapted movement solution. Future research should continue in this direction to better understand the relation between individual learning dynamics and the learning outcomes in self-controlled practice.

Conclusion

Encouraging the learner's search of the perceptual-motor workspace through task variations during practice is thought to facilitate learning. Our study showed that in the context of a complex multi-articular task such as climbing, learners may not benefit more from task variations than from constant practice, probably because of the richness of the constant practice condition. However, simply giving the learners the possibility to choose when to confront new task variations seems to enable them to search the perceptual-motor workspace more efficiently and develop behavioral flexibility.

Supplementary Information

Table 11. Results of the post-hoc tests for the significant fixed effects of the GLMM applied to cluster 1.

Contrast	log odds ratio	SE	z ratio	p-value
Group effect				
CPG vs. IVG	0.68	0.56	1.21	.682
CPG vs. SVG	**1.47**	**0.56**	**2.61**	**.027**
IVG vs. SVG	0.79	0.56	1.41	.478
	Session effect			
Pretest vs. Posttest	**2.92**	**0.39**	**7.60**	**<.001**
Pretest vs. Retention	**2.96**	**0.38**	**7.73**	**<.001**
	Route x Instruction effect			
NR-No vs. RR-No	**1.94**	**0.59**	**3.31**	**.017**
NR-No vs. AR-No	0.15	0.50	0.31	1.000
RR-No vs. AR-No	**-1.79**	**0.59**	**-3.02**	**.045**
NR-Alt vs. RR-Alt	0.48	0.49	0.98	1.000
NR-Alt vs. AR-Alt	0.91	0.51	1.78	1.000
RR-Alt vs. AR-Alt	0.43	0.51	0.83	1.000
NR-Rep vs. RR-Rep	2.21	1.14	1.94	.941
NR-Rep vs. AR-Rep	1.31	0.82	1.60	1.000
RR-Rep vs. AR-Rep	-0.90	1.23	-0.73	1.000
RR-No vs. RR-Alt	**-1.82**	**0.59**	**-3.11**	**.033**
RR-Alt vs. RR-Rep	**4.09**	**1.10**	**3.70**	**.004**
RR-No vs. RR-Rep	2.27	1.13	2.01	.808
AR-No vs. AR-Alt	0.40	0.52	0.77	1.000
AR-Alt vs. AR-Rep	**2.76**	**0.77**	**3.58**	**.006**
AR-No vs. AR-Rep	**3.16**	**0.77**	**4.09**	**<.001**
NR-No vs. NR-Alt	-0.36	0.48	-0.73	1.000
NR-Alt vs. NR-Rep	**2.36**	**0.60**	**3.95**	**.001**
NR-No vs. NR-Rep	**2.00**	**0.60**	**3.35**	**.014**

Note: SE: standard error of the log odd ratio value; p-values are adjusted with a Bonferroni correction, significant p-values are in bold characters. CPG: constant practice group; IVG: imposed variability group; SVG: self-controlled variability group. NR: neutral route; AR: alternation route; RR: repetition route. No: condition without additional instruction; Alt: condition with instruction to perform hand alternation as much as possible; Rep: condition with instruction to perform hand repetition as much as possible.

Table 12. Results of the post-hoc tests for the significant fixed effects of the GLMM applied to cluster 3.

Contrast	log odds ratio	SE	z ratio	p-value
	Session effect			
Pretest vs. Posttest	**1.85**	**0.42**	**4.38**	**<.001**
Pretest vs. Retention	**1.92**	**0.42**	**4.59**	**<.001**
	Instruction effect			
No vs. Alt	0.34	0.59	0.58	1.000
No vs. Rep	**-3.36**	**0.48**	**-6.95**	**<.001**
Alt vs. Rep	**-3.70**	**0.53**	**-6.96**	**<.001**

Note: SE: standard error of the log odd ratio value; p-values are adjusted with a Bonferroni correction, significant p-values are in bold characters. No: condition without additional instruction; Alt: condition with instruction to perform hand alternations as much as possible; Rep: condition with instruction to perform hand repetition as much as possible.

Table 13. Results of the post-hoc tests for the significant fixed effects of the GLMM applied to cluster 4.

Contrast	log odds ratio	SE	z ratio	p-value
	Session effect			
Pretest vs. Posttest	**-2.09**	**0.46**	**-4.50**	**<.001**
Pretest vs. Retention	**-1.98**	**0.50**	**-4.01**	**<.001**
	Route effect			
NR vs. RR	**2.99**	**0.44**	**6.87**	**<.001**
NR vs. AR	**-0.95**	**0.39**	**-2.46**	**.042**
RR vs. AR	**-3.95**	**0.50**	**-7.92**	**<.0001**
	Instruction effect			
No vs. Alt	**-1.33**	**0.35**	**-3.85**	**<.001**
No vs. Rep	**4.58**	**0.55**	**8.28**	**<.001**
Alt vs. Rep	**5.91**	**0.63**	**9.40**	**<.001**
	Group x Session effect			
CPG-Pretest vs. IVG-Pretest	-2.61	1.19	-2.20	.417
IVG-Pretest vs. SVG-Pretest	-0.67	0.99	-0.68	1.000
CPG-Pretest vs. SVG-Pretest	-3.28	1.16	-2.84	.068
CPG-Posttest vs. IVG-Prosttest	-0.23	1.10	-0.21	1.000
IVG-Posttest vs. SVG-Posttest	-0.85	1.04	-0.82	1.000
CPG-Posttest vs. SVG-Posttest	-1.09	1.09	-1.00	1.000
CPG-Retention vs. IVG-Retention	1.25	1.16	1.07	1.000
IVG-Retention vs. SVG-Retention	-1.73	1.12	-1.55	1.000
CPG-Retention vs. SVG-Retention	-0.49	1.11	-0.44	1.000
CPG-Pretest vs. CPG-Posttest	**-3.61**	**0.89**	**-4.06**	**<.001**
CPG-Pretest vs. CPG-Retention	**-4.20**	**0.93**	**-4.51**	**<.001**
IVG-Pretest vs. IVG-Posttest	-1.23	0.64	-1.92	.817
IVG-Pretest vs. IVG-Retention	-0.34	0.73	-0.47	1.000
SVG-Pretest vs. SVG-Posttest	-1.43	0.58	-2.43	.225
SVG-Pretest vs. SVG-Retention	-1.41	0.63	-2.24	.380

Contrast	log odds ratio	SE	z ratio	p-value
	Route x Session effect			
NR-Pretest vs. NR-Posttest	**-2.69**	**0.672**	**-4.005**	**<.001**
NR-Pretest vs. NR-Retention	**-2.77**	**0.728**	**-3.811**	**.002**
RR-Pretest vs. RR-Posttest	-0.74	0.781	-0.945	1.000
RR-Pretest vs. RR-Retention	0.26	0.846	0.312	1.000
AR-Pretest vs. AR-Posttest	**-2.84**	**0.653**	**-4.343**	**<.001**
AR-Pretest vs. AR-Retention	**-3.45**	**0.742**	**-4.642**	**<.001**
NR-Pretest vs. RR-Pretest	1.33	0.646	2.061	.589
NR-Pretest vs. AR-Pretest	-0.68	0.524	-1.293	1.000
RR-Pretest vs. AR-Pretest	**-2.01**	**0.638**	**-3.150**	**.025**
NR-Posttest vs. RR-Posttest	**3.28**	**0.689**	**4.764**	**<.001**
NR-Posttest vs. AR-Posttest	-0.82	0.656	-1.257	1.000
RR-Posttest vs. AR-Posttest	**-4.11**	**0.760**	**-5.403**	**<.001**
NR-Retention vs. RR-Retention	**4.37**	**0.796**	**5.489**	**<.001**
NR-Retention vs. AR-Retention	-1.35	0.786	-1.718	1.000
RR-Retention vs. AR-Retention	**-5.72**	**0.956**	**-5.978**	**<.001**
	Session x Instruction effect			
No-Pretest vs. Alt-Pretest	-0.48	0.49	-0.98	1.000
No-Pretest vs. Rep-Pretest	**2.64**	**0.84**	**3.15**	**.024**
Alt-Pretest vs. Rep-Pretest	**3.12**	**0.84**	**3.73**	**.003**
No-Posttest vs. Alt-Posttest	**-1.97**	**0.61**	**-3.22**	**.019**
No-Posttest vs. Rep-Posttest	**4.62**	**0.80**	**5.76**	**<.001**
Alt-Posttest vs. Rep-Posttest	**6.59**	**0.94**	**7.01**	**<.001**
No-Retention vs. Alt-Retention	-1.56	0.65	-2.40	.247
No-Retention vs. Rep-Retention	**6.47**	**1.06**	**6.09**	**<.001**
Alt-Retention vs. Rep-Retention	**8.03**	**1.19**	**6.73**	**<.001**
No-Pretest vs. No-Posttest	**-2.25**	**0.56**	**-4.04**	**<.001**
No-Pretest vs. No-Retention	**-2.90**	**0.61**	**-4.77**	**<.001**
Alt-Pretest vs. Alt-Posttest	**-3.74**	**0.63**	**-5.90**	**<.001**
Alt-Pretest vs. Alt-Retention	**-3.98**	**0.69**	**-5.80**	**<.001**
Rep-Pretest vs. Rep-Posttest	-0.27	1.04	-0.26	1.000
Rep-Pretest vs. Rep-Retention	0.93	1.18	0.79	1.000

Note: SE: standard error of the log odd ratio value; p-values are adjusted with a Bonferroni correction, significant p-values are in bold characters. CPG: constant practice group; IVG: imposed variability group; SVG: self-controlled variability group. NR: neutral route; AR: alternation route; RR: repetition route. No: condition without additional instruction; Alt: condition with instruction to perform hand alternations as much as possible; Rep: condition with instruction to perform hand repetitions as much as possible.

Table 14. Results of the post-hoc tests for the significant fixed effects of the GLMM applied to cluster 5.

Contrast	log odds ratio	SE	z ratio	p-value
	Session effect			
Pretest vs. Posttest	**-3.21**	**0.45**	**-7.20**	**<.001**
Pretest vs. Retention	**-3.26**	**0.45**	**-7.29**	**<.001**
	Route effect			
NR vs. RR	**-2.88**	**0.40**	**-7.26**	**<.001**
NR vs. AR	0.60	0.37	1.63	0.310
RR vs. AR	**3.47**	**0.43**	**8.07**	**<.001**
	Instruction effect			
No vs. Alt	**2.59**	**0.46**	**5.67**	**<.001**
No vs. Rep	**-2.31**	**0.34**	**-6.74**	**<.001**
Alt vs. Rep	**-4.90**	**0.53**	**-9.26**	**<.001**

Note: SE: standard error of the log odd ratio value; p-values are adjusted with a Bonferroni correction, significant p-values are in bold characters. NR: neutral route; AR: alternation route; RR: repetition route. No: condition without additional instruction; Alt: condition with instruction to perform hand alternations as much as possible; Rep: condition with instruction to perform hand repetitions as much as possible.

Chapter 6: Effects of Practice Conditions on Performance

Introduction

When learners are practicing under constant conditions, it appears that they may show different performance dynamics. For instance, Liu et al. (2006) examined the performance dynamics of participants practicing a roller-ball task until reaching a learning criterion (i.e., being successful during 30s in 8 out of 10 trials). In the second experiment, out of 11 participants, three never reached the learning criterion in seven sessions of practice (including 50 to 60 trials each). The remaining eight participants reached the learning criterion, but the number of necessary trials ranged from 10 to 291. Similar observations were made in a climbing task, where authors observed that some learners may demonstrate progressive improvements or sudden improvements in their performances, while one participant continuously failed to climb the route (Orth, Davids, Chow, et al., 2018). These studies showed that while for some participants the discovery of an appropriate task solution was almost immediate during practice, others needed a larger amount of practice, or, in some cases, an adaptation of the task to demonstrate improvements. Thus, developing learning protocols fostering exploration appears necessary to avoid leaving some learners behind.

Learning theories grounded in the dynamical system perspective and the ecological approach to perception and action proposed that variable practice conditions would facilitate the learning processes (Davids et al., 2012). The differential learning approach to skill acquisition proposed that adding external noise to movements would support the discovery of functional movement solutions to achieve the task to-be-learned (Schöllhorn et al., 2006, 2009). With the noise added through random variations of multiple task parameters, learners are encouraged to explore a larger panel of the perceptual-motor workspace, which would help escape local minima (e.g., preferred initial behavioral tendencies) and discover new behavioral solutions (Schöllhorn et al., 2006, 2009). This random variability would improve the learners' performances on retention and transfer tests in comparison to repetitive practice conditions (Schöllhorn et al., 2009). However, Hossner, Käch, & Enz (2016) proposed that more structured variability in practice would be more effective than random variability (such as in a differential learning protocol) to improve skill acquisition. Structured variations in their study protocol consisted of varying some task parameters while keeping other task parameters constant between trials. Their results suggested that participants following a structured learning protocol better improved their performance in a shot-put task than participants in the differential learning group. Thus, reducing the inter-trials variability by giving participants more common task space between trials appears to benefit learning (Hossner et al., 2016).

In perceptual learning studies, the variations of task parameters during practice was also hypothesized to benefit learning in comparison to constant practice (e.g., Fajen & Devaney, 2006; Huet et al., 2011). This benefit of variations of task parameters was explained by the reduction of the usefulness of initially used informational variables to guide action, and the discovery of other informational variables that were more reliable in the different conditions experienced during practice (Fajen & Devaney, 2006). For this effect to be effective, the varied task parameters must be related to the initially used informational variable, thus, the direction of learning may change according to the varied task parameter. For instance, Huet et al. (2011) showed that learners better performed in transfer test conditions where the same task parameters as in practice were varied than when other task parameters were varied. Therefore, the generalization of learning was specific to the task parameter that was varied during practice. Thus, not only does variability in practice foster learner's discovery of new behavioral solutions, but it also guides exploration in terms of information pick-up by directing the learners toward more reliable information for action.

Both the dynamical system perspective and the ecological approach to perception and action suggest that variability in practice conditions would improve performance in the practiced task (Schöllhorn et al., 2006) and would improve generalization of learning (Huet et al., 2011) in comparison to a repetitive practice condition. However, the amount of practice offered to the individuals to explore the set of constraints (i.e., the potential of task variations) also affects the learning process. More particularly, the discovery of adapted task solutions during practice affects the learners' ability to transfer their experience to new contexts (Pacheco & Newell, 2015a), and a crucial feature for learners to discover task solutions is the relation between their skill level and the task demands (Liu, Mayer-Kress, & Newell, 2006, 2010). Although the task demands do not change from an observer point of view, the learners' skill level change over time as learners explore the offered task space through practice, but this time differs between individuals as illustrated by Liu et al. (2006) with the rollerball task. A solution proposed to individualize the amount of practice given on each task variation during variable practice is to develop self-controlled practice, where individuals can choose when to be confronted to a novel task variation. Such practice was shown to be efficient when learners controlled the task difficulty of a rollerball task (Liu, Luo, Mayer-Kress, & Newell, 2012). By giving participants the opportunity to choose when and how to change the task difficulty (i.e., by increasing or decreasing the initial ball speed), results showed that participants were more successful during practice and demonstrated better improvement rate than groups who had followed an intervention with a progressively increasing task difficulty (Y.-T. Liu et al., 2012). These results suggest that self-controlled practice enabled participants to better adapt to the different levels of difficulty, whereas the other groups could not cope with the rate at which difficulty increased. A possible explanation is that being able to change the practice conditions enable learners to escape from unsuccessful conditions which would help to maintain their engagement in the learning process (e.g., Liu et al., 2012). Conversely, learners who quickly find a task solution can be challenged by a new variation of the task, which would stimulate more exploration. Thus, self-controlled practice where learners can choose the amount of practice in the different task conditions may possibly help to enhance learners' active self-regulation during performance by promoting their engagement with their learning environment, which should in return facilitate adaptation to new performance context (Woods, Rudd, Robertson, & Davids, 2020).

Current study

The first aim of this study was to examine whether practice with variations of a complex perceptual-motor task (i.e., variable practice) would affect performances and behavioral variability. We expected that variable practice would increase behavioral variability during practice in comparison to constant practice, which would improve the learning rate (faster improvement in performances) and most importantly would improve performance during a transfer test.

A second aim was to examine whether outcomes of variable practice can be improved by giving participants the opportunity to control the amount of practice on each task variation in comparison to participants for whom variations were imposed. We expected that the self-controlled practice condition would facilitate individual adaptations in comparison to the imposed practice condition, which would induce greater inter-individual differences in learning outcomes. Therefore, the facilitation of individual adaptations to the learning environment would lead to greater improvement in performances and transfer for the self-controlled condition.

Method

Participants

Twenty-four participants volunteered to participate in the experiment, but two dropped out after the first session. The participants were assigned to either a constant practice group (CG, n = 7), an imposed variability group (IVG, n= 7) or a self-controlled variability group (SVG, n = 8). The participants' skill level was in the lower grade group according to the International Rock Climbing Research Association scale (Draper et al., 2015). The protocol was explained to all the participants, who then provided written informed consent to participate in this study before starting the first session.

Learning Protocol

Participants attended 10 learning sessions over 5 weeks (2 sessions per week). The participants in the CG always climbed the same route, called the control route (84 trials in total). The participants in the IVG practiced on the control route and nine subsequent variations of the control route. Thus, the IVG practiced on a new variation of the training route in each session. The SVG followed the same protocol as the IVG with the difference that, at the end of the sessions 2 to 9, they were asked whether they wanted to continue practicing on the same route or if they wanted to change the route on which they performed the highest number trials. Thus, they could follow the same protocol as the IVG if they always chose to change the variant route after each session. Pictures of the routes are available in **Appendix A**.

The task goal for all trials was to climb the route as fluently as possible while using all the handholds of the route and using them in a bottom-up order. These prompts were told before each trial. Participants received a feedback about their climbing fluency after each session.

Data Collection

Trials were filmed at 30 fps and 1920x1080 pixels frames with two GoPro 5 cameras (GoPro Inc. ®, San Mateo, CA, USA), each camera captured the entire wall. A red light was positioned on the back of the participants' harness.

The videos of the cameras were imported in Kinovea© (version 0.8.25, Boston, MA, USA). The lens distortion was corrected by importing the intrinsic parameters of the cameras' lens in Kinovea from Agisoft lens (version 0.4.1, Agisoft LLC, Saint Petersburg, Russia). Then, a manually set grid was used to correct the perspective and to calibrate the distances by using markers placed on the climbing routes. The light on the back of the participant was then tracked from the frame with the first movement of the participant until the moment the climber touched the last handhold of the route. From this tracking, the projected coordinates of the hip position on the 2D wall were computed for each frame of the video.

Data Analysis

Performance

The coordinates of the hip position were used to compute the geometric index of entropy (GIE). The GIE was designed as a measure of performance that reflects the degree of coherence in information-movement couplings (Cordier et al., 1994). The GIE enables assessment of the degree of complexity of the hip trajectory. A complex hip trajectory would reflect a poor sensitivity of the climber to the task constraints, whereas a smooth trajectory would reflect fluent climbing movements. GIE is calculated with the following equation:

$$GIE = \log_2(\frac{2L}{c})$$

Where L is the length of the hip trajectory and c the perimeter of the convex hull around the hip trajectory. Data analyses to obtain the GIE values were performed with Matlab R2014a® software (version 8.3.0.532, The MathWorks Inc., Natick, MA, USA).

Behavioral Variability

The trajectories of the hip on the control route were compared to obtain a measure of variability between trials. To do so, the time series of the x and y position of the hip on each trial were normalized using a z-score transformation and a similarity index was obtained for each pair of trials with dynamic time warping (DTW). DTW allows to compare time series with different lengths by creating a distance matrix containing the distance between each point of the two time series (Cleasby et al., 2019). Then, the best alignment between the time series corresponds to the minimum cumulative distance (i.e., the warping path) obtained through the distance matrix (see **Figure 19** in the **Supplementary Information**). This cumulative distance is then normalized by the lengths of the time series (Giorgino, 2009). This normalized similarity index value was used to quantify variations in participants' hip trajectories on the control route (i.e., their behavioral variability). Similar use of DTW method was performed in Ossmy and Adolph (2020). DTW was performed in R (version 3.6.1, R Core Team, 2019) with the DTW package (Giorgino, 2009) and the TSclust package (Montero & Vilar, 2014).

Data Processing and Dependent Variables

Learning Improvement

Improvement rates were calculated for each route (i.e., control route, variant routes, and transfer route) and participants, using the difference between the GIE in the first trial on a route and the GIE in the last trial on the same route. Then the difference was divided by the GIE score on the first trial. Therefore, the improvement rate corresponded to a normalized amount of improvement.

Learning Rate

For each participant, two exponential models were fitted to the GIE scores. The first model aimed to examine the effect of the practice conditions on the performance on the control route. Therefore, individual models were fitted to the mean GIE scores on the first three trials of each session (which were common to the three practice conditions). The second model aimed to examine the effect of the different practice conditions on the participants' performance during the entire protocol. Thus, individual models were fitted to the GIE scores on the 84 trials performed.

The two models were fitted for each participant with a three-parameter exponential equation:

$$F(t) = \alpha + \beta\, e^{-\lambda t}$$

with α the asymptotic value, β the range of progression, λ the learning rate and t the practice time (Y.-T. Liu, Mayer-Kress, & Newell, 2003). All the models were fitted with the "nls" function in R (R Core Team, 2019).

Behavioral Variability

Using the normalized index obtained with the DTW method, the initial and final behavioral variability of each participant was calculated. The initial behavioral variability corresponded to the mean of the normalized similarity index on the trials of sessions 1 and 2. Final behavioral variability was computed as the mean of the normalized similarity index on the trials of the sessions 9 and 10.

The amount of behavioral variability displayed by participants during the learning protocol was calculated as the individual mean of the normalized similarity index in all the trials.

Statistical Analysis

Learning Improvement

A potential group effect on the improvement rates on the control route and the transfer route were tested with a one-way ANOVA. P-values of the post-hoc comparisons were adjusted with a Bonferroni correction. The improvement rates of the IVG and the SVG on the variant routes were compared with a t-test for independent groups.

Learning Rate

To examine whether the practice conditions affected the performance curves, one-way ANOVAs were performed followed by post-hoc tests with p-values adjusted with a Bonferroni correction. When a parameter did not respect the assumption of normality, the ANOVA was replaced by a Kruskal-Wallis test followed by Mann-Whitney tests.

Behavioral Variability

A two-way repeated measures ANOVA was planned to examine the potential Practice (initial vs. final behavioral variability) and Group effect on the behavioral variability. However, as Levene's test was significant for the final behavioral variability [$F(2,18) = 7.81$, $p = .004$], a paired t-test was performed to assess the effect of Practice. To examine whether change in behavioral variability was different between Groups, a one-way ANOVA was performed on the individual difference between Final and Initial behavioral variability. As two tests were used instead of one, a Bonferroni correction was applied, which set significance threshold at .025.

Concerning the amount of behavioral variability experienced by participants during the learning protocol, a one-way ANOVA was performed to examine a potential Group effect.

In the event of a nonsignificant result in the main analysis, we also performed the Bayesian version of the analysis and reported the Bayes factors (*BF*) to assess the evidence in favor of the null or the alternative hypothesis (Dienes, 2014, 2016).

Relationship between Learning Improvement and Behavioral Variability

Previous studies showed that initial intertrial variability was positively correlated with performance improvement (Haar, van Assel, & Faisal, 2020). This relationship was tested in the current study with a Pearson's correlation performed on the mean behavioral variability over the first half of practice (i.e., sessions 1 to 5) and the improvement rate on the control route.

Results

Improvement Rates on the Control Route

Participant 2 from the CG was excluded from the analyses as she dropped out of the study after the fourth learning session. The ANOVA performed on the improvement rates on the control route showed a large effect of the group factor [$F(2,18) = 11.39$, $p < .001$, $\eta_G^2 = .56$]. The post-hoc tests revealed that the improvement rate was more important for the CG [$M = .61$, $SD = .07$] than for the IVG [$M = .48$, $SD = .05$] ($p = .006$) and the SVG [$M = .45$, $SD = .07$] ($p < .001$) but the improvement rate did not significantly differ between the IVG and the SVG ($p = 1$) (**Figure 14A**). Individual improvement rates (**Table 15**) showed that all the participants from the three learning groups improved their climbing fluency on the control route between the first and tenth learning session. All participants in the CG showed improvement rate above .54 while in the IVG and SVG, only one participant showed improvement rate this high.

Table 15. Individual improvement rates on the control route.

Group	Individual Participant							
	1	2	3	4	5	6	7	8
CG	.596	-	.554	.541	.578	.687	.696	
IVG	.473	.445	.531	.524	.385	.450	.525	
SVG	.447	.470	.466	.490	.360	.380	.580	.374

Note: The improvement rate of the participant 2 from CG could not be calculated as she dropped out of the study after the fourth learning session.

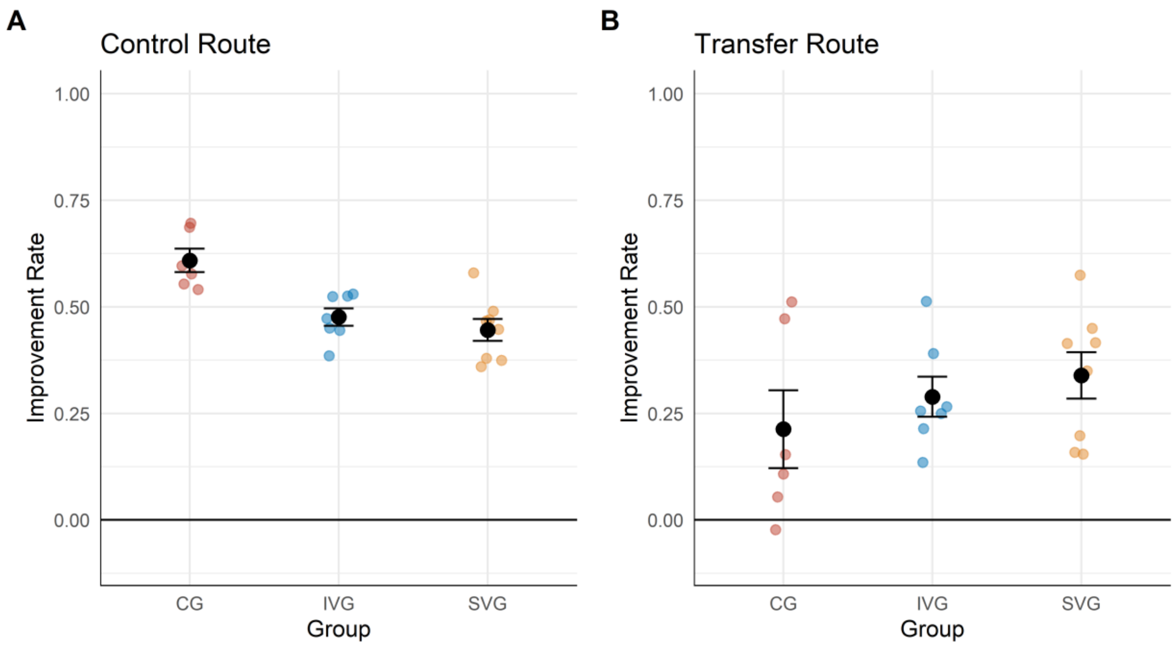

Figure 14. Improvement rates on the control (A) and transfer (B) route.
Colored points represent individual values. Black point and error bar show group mean and standard error. CG, IVG and SVG refer to the constant practice group, imposed variability group and self-controlled variability group, respectively.

Improvement Rates on the Variant Routes

The individual improvement rate on the variant routes (**Table 16**) showed important variability within participants for the two groups. Only two participants (participants 4 and 7) of the IVG and two participants (participants 2 and 8) of the SVG showed no negative improvement rate, the other 11 participants showed negative improvement rates on one to four variant routes. The t-test used to compare the mean improvement rate on variants of the IVG (M = .14, SD = .08) and the SVG (M = .11, SD = .06) [$t(13) = 0.73$, p = .477] did not show any significant difference. Bayesian independent samples t-test suggests anecdotal evidence in favor of the absence of difference between the two groups (BF = 0.52).

Table 16. Individual improvement rates on variant routes.

Variant Routes	Individual Participant							
	1	2	3	4	5	6	7	8
			Imposed Variability Group					
V1	.147	.220	-.191	.352	-.007	.284	.160	
V2	.270	.0625	.081	.137	-.055	.206	.376	
V3	.065	.276	-.039	.020	.277	.434	.118	
V4	.091	.286	.200	.457	.340	.041	.152	
V5	-.042	.308	.270	.135	.072	.095	.380	
V6	-.018	.316	.077	.318	-.274	.317	.273	
V7	.336	.0916	-.071	.352	.066	.145	.039	
V8	-.032	-.064	.226	.074	.042	-.021	.409	
V9	.217	-.041	.028	.157	-.236	-.112	.208	
			Self-Controlled Variability Group					
V1	.292	.244	.332	.293	-.023	.257	.351	**.222**
V2	.064	.251	.043	.215	.188	-.153	.340	.173
V3	-.011	.048	.239	-.034	.298	-.047	.016	.135
V4	.194	.031	-.143	.049	.450	.057	.062	.104
V5	.393	.157	.051	.178	.296	.280	.031	.166
V6	-.138	.080	.017	.023	.084	-.004	-.094	.133
V7	.207	.302	-.029	.210	/	/	-.257	.058
V8	/	.146	-.083	.249	/	/	.072	/
V9	/	/	*.043*	*.056*	/	/	/	/

Note: Bold value indicates that the climbing fluency on the first trial was missing and the value on the second trial was used to calculate the improvement rate. Italic values indicate that participant performed only three trials on the climbing route. / indicates that participant did not practice on the corresponding variant.

Improvement Rate on the Transfer Route

The ANOVA performed on the improvement rates on the transfer route (**Figure 14B**) did not show significant group effect [$F(2,18) = 0.97$, $p = .399$, $\eta^2 = 0.10$] and the Bayesian factor suggest anecdotal evidence in favor of the absence group effect ($BF = 0.46$). Among all the participants, only one participant in the CG showed a negative improvement rate, while the other participants improved their climbing fluency with practice (**Table 17**).

Table 17. Individual improvement rates on the transfer route.

Group	Individual Participant							
	1	2	3	4	5	6	7	8
CG	-.023	-	.054	.512	.154	.108	.472	
IVG	.255	.390	.266	.513	.134	.215	.249	
SVG	.449	.155	.198	.350	.159	.574	.414	.416

Note: The improvement rate of the participant 2 from CG could not be calculated as she dropped out of the study after the 4th learning session.

Performance Curves on the Control Route

Three-parameter exponential models were fitted to participants' mean fluency scores in the 10 learning sessions. The model could not be fitted to one participant in each group. The **Figure 15** displays the individual performance curves and the group performance curve obtained with the mean values of the individual model parameters (**Table 18**). The ANOVA applied to the individual alpha parameters did not reveal a significant group effect [$F(2,15) = 1.01$, $p = .387$, $\eta_G^2 = .12$] and the Bayesian ANOVA showed anecdotal evidence in favor of the hypothesis that the three groups reached similar climbing fluency at the end of the protocol (*BF* = 0.50).

The individual beta parameters did not follow a normal distribution according to the Shapiro-Wilk test, thus non-parametric Kruskal Wallis test was applied to test the group effect. Results showed a significant group effect [$\chi^2(2) = 6.42$, $p = .040$]. Follow-up Mann-Whitney tests showed no significant differences between CG and IVG [$W = 23.00$, $p = .177$] and between IVG and SVG [$W = 14.00$, $p = .366$], but it revealed that the CG showed a significantly higher improvement than the SVG [$W = 33.00$, $p = .010$].

The individual lambda parameters also did not follow a normal distribution according to the Shapiro-Wilk test. The Kruskal Wallis test did not show between groups differences [$\chi^2(2) = 1.79$, $p = .409$] and Bayesian ANOVA showed anecdotal evidence in favor of the hypothesis that three groups had a similar learning rate (*BF* = 0.42). Values of the parameters are shown in **Table 18**. The standard deviation of the beta and lambda parameters suggest lower inter-individual variability in the performance curves for the SVG than for the two other groups.

The ANOVA performed on the r-squared values did not reveal a group effect on the models fit [$F(2,15) = 0.36$, $p = .707$, $\eta_G^2 = .045$] and the Bayesian ANOVA showed anecdotal evidence in favor of the null hypothesis (*BF* = 0.35).

Table 18. Individual parameter values and fit of the exponential function.

Participant ID	α	β	λ	R^2
Constant Practice Group				
P1	0.597	2.104	1.383	.855
P3	0.468	0.785	0.371	.881
P5	0.639	1.717	0.569	.986
P6	0.370	1.064	0.420	.939
P7	0.406	1.270	0.367	.955
Mean ± SD	0.496 ±0.118	1.388 ±0.525	0.622 ±0.433	.924 ±.054
Imposed Variability Group				
P1	0.618	0.887	0.248	0.893
P2	0.533	0.663	0.262	0.975
P3	0.685	0.771	0.378	0.941
P5	0.473	0.434	0.220	0.722
P6	1.007	2.357	1.707	0.834
P7	0.425	0.813	0.582	0.929
Mean ± SD	0.623 ±0.210	0.988 ±0.689	0.566 ±0.574	.882 ±.092
Self-controlled Variability Group				
P1	0.523	0.417	0.302	0.733
P2	0.615	0.829	0.418	0.939
P3	0.499	0.565	0.334	0.984
P4	0.551	0.723	0.622	0.933
P6	0.324	0.637	0.111	0.839
P7	0.615	1.039	0.395	0.948
P8	0.652	0.530	0.355	0.938
Mean ± SD	0.540 ±0.110	0.677 ±0.208	0.363 ±0.152	.902 ±.087

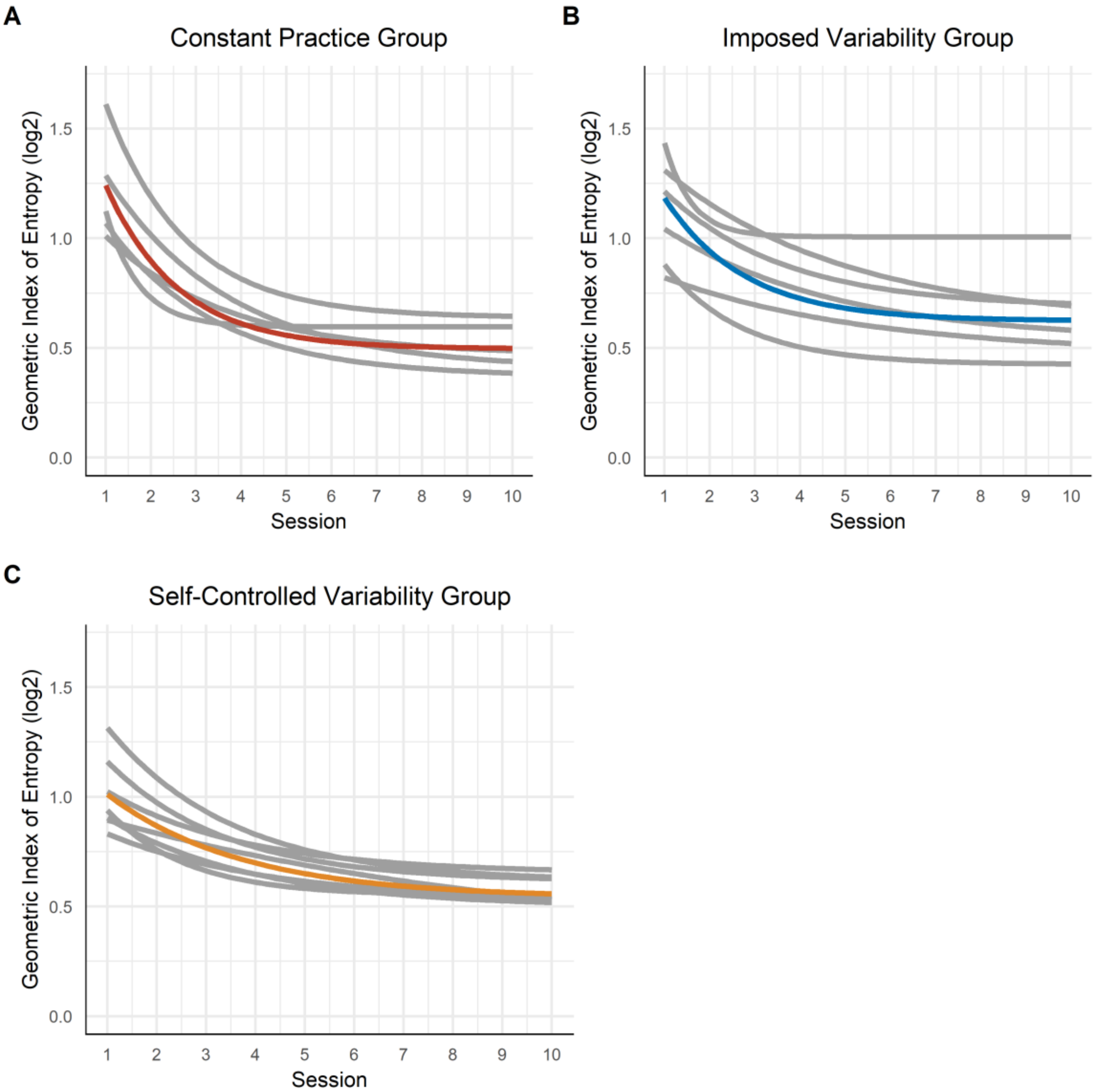

Figure 15. Learning curves on sessions 1 to 10 on the control route.
The curves were fitted with the three-parameter exponential model. Gray lines refer to individual participants' learning curves and colored lines refer to the groups' mean learning curves.

For the three remaining participants (i.e., participant 4 in CG. participant 4 in IVG and participant 5 in SVG), piecewise linear regression fitted their fluency scores, showing that they demonstrated initially no to poor improvements in climbing fluency before the breakpoint, then the slope of their performances steepened. In the **Supplementary Information**, the individual learning curves in the control route can be seen in **Figure 23**, **24** and **25** and the parameters of the used functions are presented in **Table 20** and **21**.

Performance Curves on all the Routes (i.e., 84 trials)

Three parameters exponential models were fitted to the participants' fluency scores obtained in their 84 trials performed during the learning sessions (**Figure 16**). The model could not be fitted to one participant in the CG and the SVG group. These two participants were excluded from the following analysis. The individual model parameters are presented in **Table 19**. The ANOVA performed on the individual alpha parameters revealed a significant group effect [$F(2,16) = 4.20$, $p = .034$, $\eta_G^2 = .34$] with a lower alpha value for the CG [$M = 0.52$, $SD = 0.11$] than for the IVG [$M = 0.76$, $SD = .18$] ($p = .034$) revealing that the CG reached a higher climbing fluency at the end of the protocol in comparison to the IVG. No significant differences were observed in the alpha value between the CG and the SVG [$M = 0.63$, $SD = 0.12$] ($p = .653$) and between the IVG and the SVG ($p = .311$).

The ANOVA performed on the individual beta parameters also revealed a significant group effect [$F(2,16) = 9.03$, $p = .002$, $\eta_G^2 = .53$] with a higher beta value for the CG [$M = 0.86$, $SD = 0.20$] than for the IVG [$M = 0.50$, $SD = .15$] ($p = .004$) and the SVG [$M = 0.51$, $SD = 0.14$] ($p = .006$) revealing that the CG showed a higher progression in climbing fluency than the two other groups. No significant differences were observed in the beta value between the IVG and the SVG ($p = 1$).

The individual lambda parameters did not follow a normal distribution according to Shapiro-Wilk test, thus a non-parametric Kruskal Wallis test was applied to test the group effect. Results did not reveal a group effect on the lambda parameter [$\chi^2(2) = 0.01$, $p = .995$] and the Bayesian ANOVA showed anecdotal evidence in favor of the hypothesis that the three groups showed similar learning rate ($BF = 0.37$).

The r-squared values of the fit of the individual model were also compared. R-squared values did not follow a normal distribution according to Shapiro-Wilk test, thus a non-parametric Kruskal Wallis test was applied to test the group effect. Results revealed a significant group effect [$\chi^2(2) = 9.22$, $p = .010$]. Follow-up Mann-Whitney U tests showed a significantly higher r-squared for the CG [$M = .78$, $SD = .13$] than for the IVG [$M = .42$, $SD = .19$] [$W = 32.00$, $p = .018$] and the SVG [$M = .50$, $SD = .09$] [$W = 35.00$, $p = .003$]. No significant difference was observed in r-squared values between IVG and SVG [$W = 33.00$, $p = .318$]. These results showed that the exponential models were better fitted to the CG than for the IVG and SVG.

Table 19. Individual parameter values and fit of the exponential function.

Participant ID	α	β	λ	R^2
Constant Practice Group				
P1	0.596	0.760	0.181	.599
P3	0.516	0.594	0.060	.673
P5	0.650	1.108	0.071	.902
P6	0.387	0.836	0.067	.862
P7	0.434	0.996	0.057	.850
Mean ± SD	0.516 ±0.109	0.859 ±0.201	0.087 ±0.053	.777 ±.133
Imposed Variability Group				
P1	0.754	0.733	0.072	.635
P2	0.594	0.494	0.050	.698
P3	0.811	0.491	0.062	.466
P4	0.954	0.424	0.047	.271
P5	0.591	0.298	0.063	.298
P6	1.025	0.646	0.113	.283
P7	0.579	0.392	0.100	.265
Mean ± SD	0.758 ±0.182	0.497 ±0.150	0.072 ±0.025	.417 ±.185
Self-controlled Variability Group				
P1	0.600	0.381	0.089	.453
P2	0.716	0.609	0.060	.552
P3	0.620	0.373	0.081	.488
P4	0.590	0.525	0.095	.481
P5	0.391	0.584	0.014	.587
P7	0.744	0.725	0.061	.592
P8	0.715	0.359	0.065	.350
Mean ± SD	0.625 ±0.120	0.508 ±0.141	0.066 ±0.027	.500 ±.086

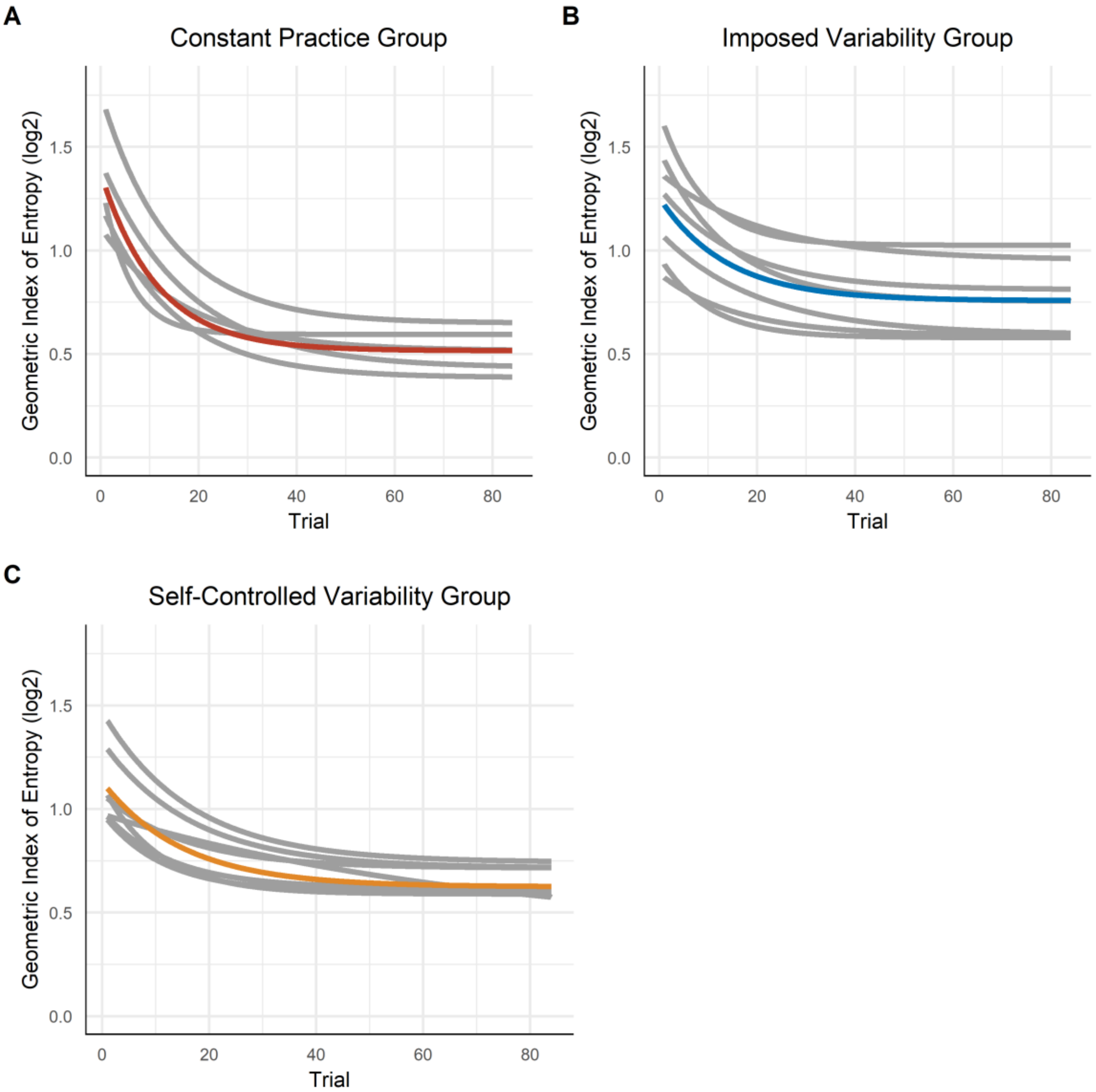

Figure 16. Learning curves of all performed trials.
The curves were fitted with the three-parameter exponential model. Gray lines refer to individual participants' learning curves and colored lines refer to the groups' mean learning curves.

Behavioral Variability

The hip trajectories and the dynamics of the behavioral variability of the participants can be seen in the **Supplementary Information** (**Figure 20, 21 and 22**). A paired t-test was performed to examine a potential difference between initial and final behavioral variability. Results showed a practice effect [$t(20) = 7.24$, $p < .001$] with higher behavioral variability on sessions 1 and 2 [$M = .19$, $SD = .05$] than on sessions 9 and 10 [$M = .12$, $SD = .04$] (**Figure 17**). To examine whether this decrease in behavioral variability was different between groups, a one-way ANOVA was performed on the differences between early (i.e., sessions 1 and 2) and late (i.e., sessions 9 and 10) behavioral variability. The results showed that the Group effect was not significant [$F(2,18) = 0.11$, $p = .900$, $\eta_G^2 = .012$], which was confirmed by a moderate evidence in favor of the null hypothesis (*BF* = 0.28).

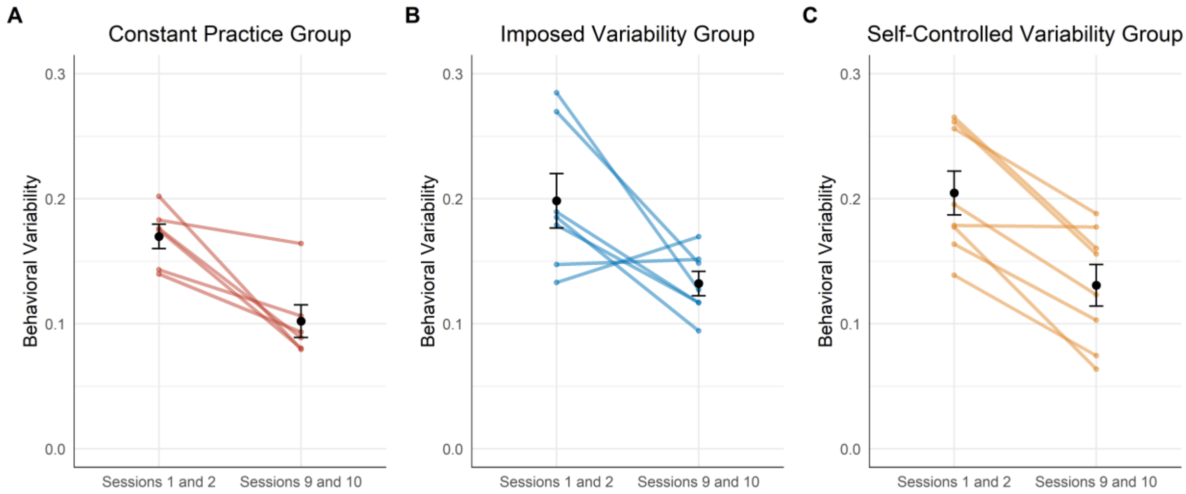

Figure 17. Mean behavioral variability in early and late practice on the control route.
Error bars show the standard error of the mean. Colored lines show the individual change in behavioral variability.

The ANOVA performed on the mean behavioral variability over the entire practice on the control route revealed a significant Group effect [$F(2,18) = 4.18$, $p = .032$, $\eta^2 = .32$]. Post-hoc tests showed that the mean behavioral variability was significantly lower for the CG [*M* = .13, *SD* = .02] than for the IVG [*M* = .17, *SD* = .03]. No significant differences were observed between the CG and the SVG [*M* = .15, *SD* = .03] or between IVG and SVG. However, post hoc comparisons of the Bayesian ANOVA showed anecdotal evidence in favor of the absence of difference between IVG and SVG (*BF* = 0.70) whereas anecdotal evidence in favor of a difference between CG and SVG was shown (*BF* = 1.17).

Relationship between Learning Improvement and Behavioral Variability

No significant correlations between participants' mean behavioral variability over the first half of practice and their improvement rate on the control route was observed [CG: $r(6) = .15$, $p = .777$; IVG: $r(7) = -.22$, $p = .629$; SVG: $r(8) = -.05$, $p = .904$] (**Figure 18**). The Bayesian correlations showed anecdotal evidence in favor of the absence of correlations between behavioral variability and improvement rate ([CG: *BF* = 0.51; IVG: *BF* = 0.51; SVG: *BF* = 0.43).

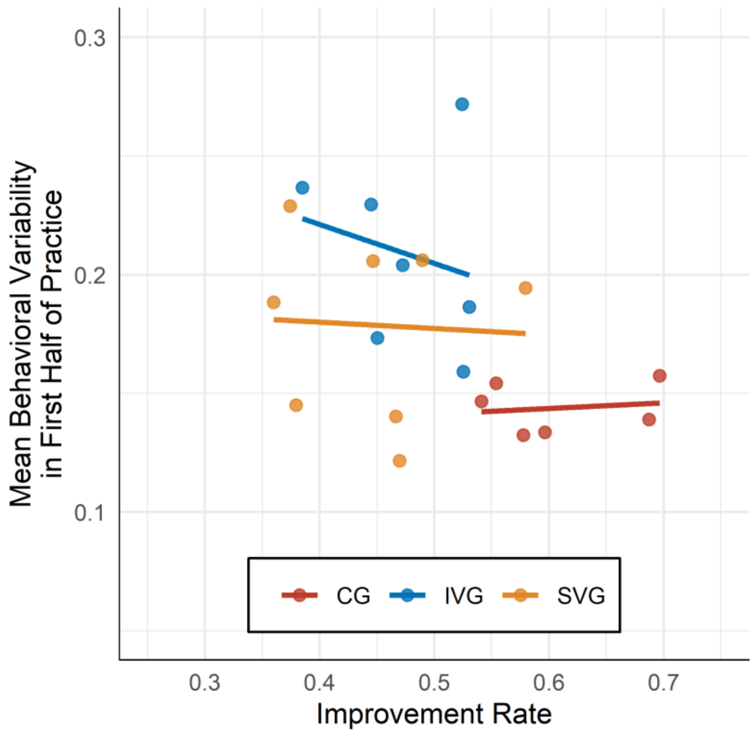

Figure 18. Relation between participants' behavioral variability and their improvement rate. Points refer to individual participant, lines to the correlation and colors to the groups. Correlations were not significant.

Discussion

The first aim of this study was to examine whether practice with variations of a complex perceptual-motor task (i.e., variable practice) would affect performances and behavioral variability. As expected, results showed that variable practice conditions yielded to higher mean behavioral variability during practice in comparison to constant practice. However, this higher variability did not benefit performance on the control route, nor the transfer route. Moreover, no significant relationship was found between behavioral variability in the first half of practice and performance improvement on the control route. A second aim was to examine whether outcomes of variable practice can be improved by giving participants the opportunity to control the amount of practice in each task variation in comparison to participants for whom the schedule of the variations was imposed. Results did not support the hypothesis that self-controlled practice improved performances in comparison to imposed schedule. However, the performance curves of the self-controlled group showed much less inter-individual variability than the two other groups, which suggest that self-controlled practice schedules were more respectful of individual learning dynamics than imposed schedules.

Increased Behavioral Variability with Practice on Task Variations

The participants assigned to the imposed and self-controlled variability groups showed higher behavioral variability in the control condition compared to the constant practice group. This result is consistent with the differential learning perspective. Indeed, according to this perspective, the practice on the variant routes would offer variability in the task constraints that would enable participants to discover novel task solutions that they would not find in constant practice conditions, where the only source of variability comes from the movement system itself (Schöllhorn et al., 2009). However, the constant practice group showed larger improvement in performance on the control route than the two groups practicing on variant routes, and the three groups showed similar improvements in performances on the transfer route. This result is not clearly in line with the differential learning perspective (Schöllhorn et al., 2006, 2009) and the variability of practice hypothesis (Schmidt, 1975), which would rather suggest that learning would benefit from increased movement variability due to task variations.

One possible explanation may be related to the nature of the variability experienced during practice. Ranganathan and Newell (2010a) showed that task variations that increased the movement variability during practice in comparison to a group that followed a constant practice protocol did not benefit learning. Indeed, the groups experiencing more movement variability showed poorer performances during practice as well as during two transfer tests (Ranganathan & Newell, 2010a). Furthermore, in another study that used the same experimental paradigm, Ranganathan and Newell (2010b) also showed that variations at the task goal level was more beneficial than task variations increasing movement variability, as the latter enabled better performances on a transfer task, although it was detrimental for performance during practice. In the current study, the task variations (the variant routes) infused variability at the task goal level, but our results showed that it also increased the movement variability on the control route. Thus, although the task variations may have helped the participants discover new task solutions, it may also have refrained participants from retaining these solutions in the control condition.

Moreover, results did not show any within-group correlation between the individuals' behavioral variability in the first half of practice and their improvement in climbing fluency on the control route. A previous study in a pool billiards task showed that initial task-relevant variability was positively correlated with performance improvement (Haar et al., 2020). However, this task-relevant variability was calculated based on the direction of the target ball, which corresponds to variability in the movement outcomes and not the movement itself, as done with the hip trajectory in our present study. When it came to variability in the movement, Haar et al. (2020) showed that performance improvement was only correlated with variability in the right elbow rotation and not with any other joint variability, which was interpreted as corresponding to the most task-relevant joint to give direction to the target ball (Haar et al., 2020). Thus, the absence of correlation between initial variability and improvement in performance in the current study may be explained by the too general level of the measure of behavioral variability. Indeed, variability in hip trajectory may be due to other events that are involved in the task completion (e.g., a change in the chain of the limbs actions or a loss of balance during the climb). Thus, the use of a measure focusing only on task-relevant variability, such as the changes in the chain of the limbs actions, may help understand the role of early exploration during practice in performance improvement.

Transfer during Practice

Our results are not consistent with those obtained in perceptual learning studies (Fajen & Devaney, 2006; Huet et al., 2011). These studies showed that in virtual reality tasks, variable practice fosters participants' attunement to more reliable information to guide their actions, and the attunement was specific to the varied task parameter. The aim of the designed task variations in the current study (the variant routes) was to enhance the participants' adaptability to different holds layouts, as it was the varied task parameter. Our results rather showed similar improvement in the transfer route for the constant practice group and the groups who practiced on task variations. Moreover, the constant practice group appears to have benefited from their extensive practice on the control route to demonstrate better climbing fluency. These results suggest that learning is specific to the environment, which the participants interact with. This would be consistent with the ecological perspective, which proposes that individuals learn by differentiating information about environmental properties, which becomes more subtle with experience in the task (J. J. Gibson & Gibson, 1955). In this perspective, skillful activity is revealed by an improved fit between the individual and the environment (Araújo & Davids, 2011). This improved fit is here illustrated by the decrease of behavioral variability during practice for the three groups, and the increased organization in the hip trajectories with practice.

However, the results also showed that participants in imposed and self-controlled schedules of task variations improved their climbing fluency across sessions on the variants. This suggests that, although no specific transfer could be observed from variants to the control route, a variant-to-variant transfer may have occurred, as characterized by better climbing fluency. As in the current study the participants were novices in climbing, the observed improvement in fluency from variant-to-variant may be due to participants' familiarization with the locomotion that climbing tasks required (i.e., the quadrupedal locomotion on a vertical plane), which would support a general transfer (Seifert, Wattebled, et al., 2013, 2016). Also, as the variants were designed to not change in difficulty level, general transfer may also be due to improvement of participants' route finding skill (Cordier, Mendès France, Bolon, & Pailhous, 1994; Cordier, Mendés France, et al., 1994). This skill refers to the climbers' ability to perceive how to chain actions on a climbing route by exploiting both the properties of the route and their own biomechanical properties (Cordier, Mendès France, et al., 1994). Thus, with practice, participants' may have strengthened their ability to perceive and act more skillfully with respect to the different holds layouts and their own internal constraints, hence facilitating the chaining of actions from variant to variant.

Two Paths in the Individual Climbing Fluency Dynamics

Results showed that most of participants' climbing fluency dynamics could be modeled with a three-parameter exponential function, as for the groups' learning curves (Y.-T. Liu et al., 2003, 2006; Newell, Liu, & Mayer-Kress, 2001). These results are in line with the observation of Orth et al. (2018) who observed that most of the participants demonstrated progressive improvement in their climbing fluency. Once again, these dynamics suggest that practice enabled improve the fit between the individual and the environment (Araújo & Davids, 2011). Then, Orth et al. (2018) also observed that few other participants showed sudden improvement in climbing fluency and they observed that one participant constantly failed to reach the top of the route. In the current study, one participant in each group showed a performance dynamic with no to poor improvement and a later abrupt progression, which was modeled with a piecewise linear regression. The dynamics of these three participants would match to the sudden improvements of the participants from Orth et al. (2018) study. The use of piecewise linear regression to model their dynamics appears interesting to identify key instants in the participants' learning curves, notably the breakpoint when the participants start improving their performance. Orth et al. (2018)

predicted that these different learning curves were due to the initial behavioral repertoire of the participants and notably their ability in using side-on and face-on body postures to climb the route. In the current experiment, the behavioral repertoire of the participants may have also influenced the different learning curves, but it did not relate to body posture as the orientation and shape of the handholds never changed and always enabled face-on body posture (which corresponds to the novices preferred body posture). In our study, the instructional constraints on hand movements (i.e., participants had to use all the handholds in a bottom-up order) required that participants perform different hand coordination patterns along the climbing route (e.g., hand repetition, hand crossing, hand alternation) that may be challenging for novices; therefore, some novices might learn new hand coordination patterns faster than others.

Self-Controlled and Imposed Practice Schedules

By giving the participants the opportunity to choose when to change the variants, the self-controlled variability group was expected to benefit more from the practice on variants by adopting a better individualized exploration/exploitation ratio than the imposed variability group (Y.-T. Liu et al., 2012). The results did not confirm this hypothesis as the self-controlled variability group showed similar learning curves and similar improvement in climbing fluency on the transfer route as the imposed variability group. Moreover, none of the participants of the self-controlled variability group chose to follow the same practice schedule as the imposed variability group but the mean performance curves of these two groups on the control route were similar. This result confirms that no specific transfer from the practice on variant routes to the practice on the control route really occurred.

Although participants in the self-controlled variability group could choose to perform more trials on the variants, the improvement in climbing fluency on these routes was not better for the self-controlled variability group compared to the imposed variability group. Results showed large intra-individual differences in improvement rate on the variant routes for the two groups, supporting that the participants used their choice to escape from unsuccessful conditions or conversely, to be challenged by a new variation of the task as in the study of Liu et al. (2012). These uses of their choice appear to help them to better cope with the variable practice in comparison to the imposed variability group. Indeed, the individual performance curves showed less interindividual variability for the self-controlled variability group than for the group with imposed schedule of task conditions. This suggests that, as expected, all the participants from the imposed variability group could not cope with the rate at which routes were changed. While it may have suited some participants, the imposed schedule may not have given sufficient time for other participants to adapt to the routes. As a consequence, these task conditions were more interfering with learning rather than fostering it. On the other hand, the choices of the self-controlled group, although being not beneficial for immediate performance, appears to have supported learning by respecting the individual learning dynamics. A potential mechanism mentioned in introduction was that self-controlled practice may encourage learners to more actively self-regulate their performances (Woods, Rudd, et al., 2020). From an ecological dynamics perspective, active self-regulation consists in interacting with the performance environment intentionally, by solving problems and engaging with constraints (Otte, Rothwell, Woods, & Davids, 2020; Woods, Rudd, et al., 2020). Self-controlled practice conditions, as designed in this study, may provide the necessary requirements for enhancing self-regulation: involving learners in the design of their practice conditions and giving them freedom to explore different movement solutions (Otte et al., 2020). However, this potential explanation needs further investigation.

Conclusion

Providing variability in practice conditions is acknowledged to benefit learning by increasing learners' exploration. Although the current study showed that experiencing task variations during practice increased behavioral variability, it did not help learners to improve their performances. On the contrary, the data rather support that exploration that enhances performance was specific to the task condition. Indeed, the participants in the constant practice condition showed the greatest performance improvements, suggesting that exploration in the variants did not benefit performance on the control route. Further understanding of the role of exploration during complex perceptual-motor task may be gained by focusing on task-relevant behavioral variability. When practicing under variable practice conditions, the individual performance dynamics suggested that imposing the schedule of the variations challenged the learners so that some had more difficulty than others to cope with the new conditions. Self-controlled schedules however appear more respectful of individual dynamics.

Supplementary Information

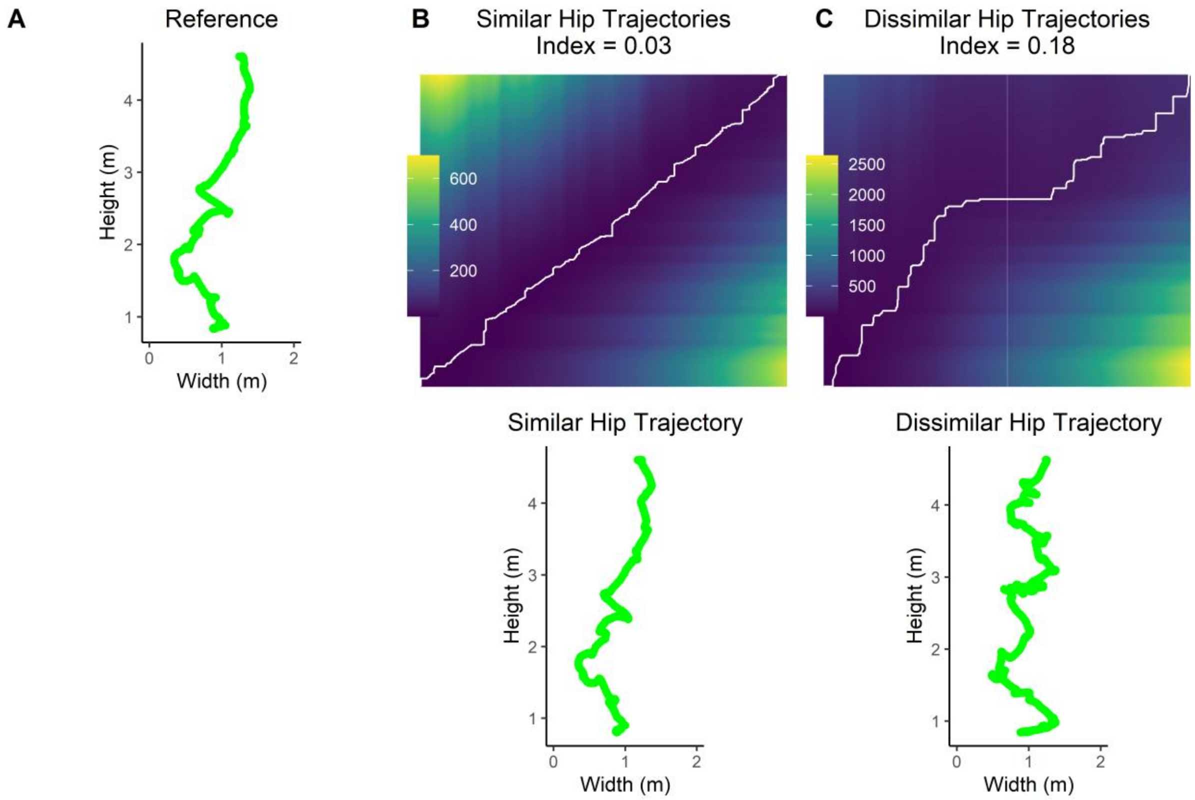

Figure 19. Dynamic time warping of hip paths.
A panel shows a hip trajectory used as reference. B panel shows a comparison of two hip paths with a high similarity. The distance matrix revealed a warping path close to the diagonal of the matrix, giving a low cumulative distance. Conversely, the C panel shows the comparison between two hip paths with a low similarity as indicated by the longer warping path.

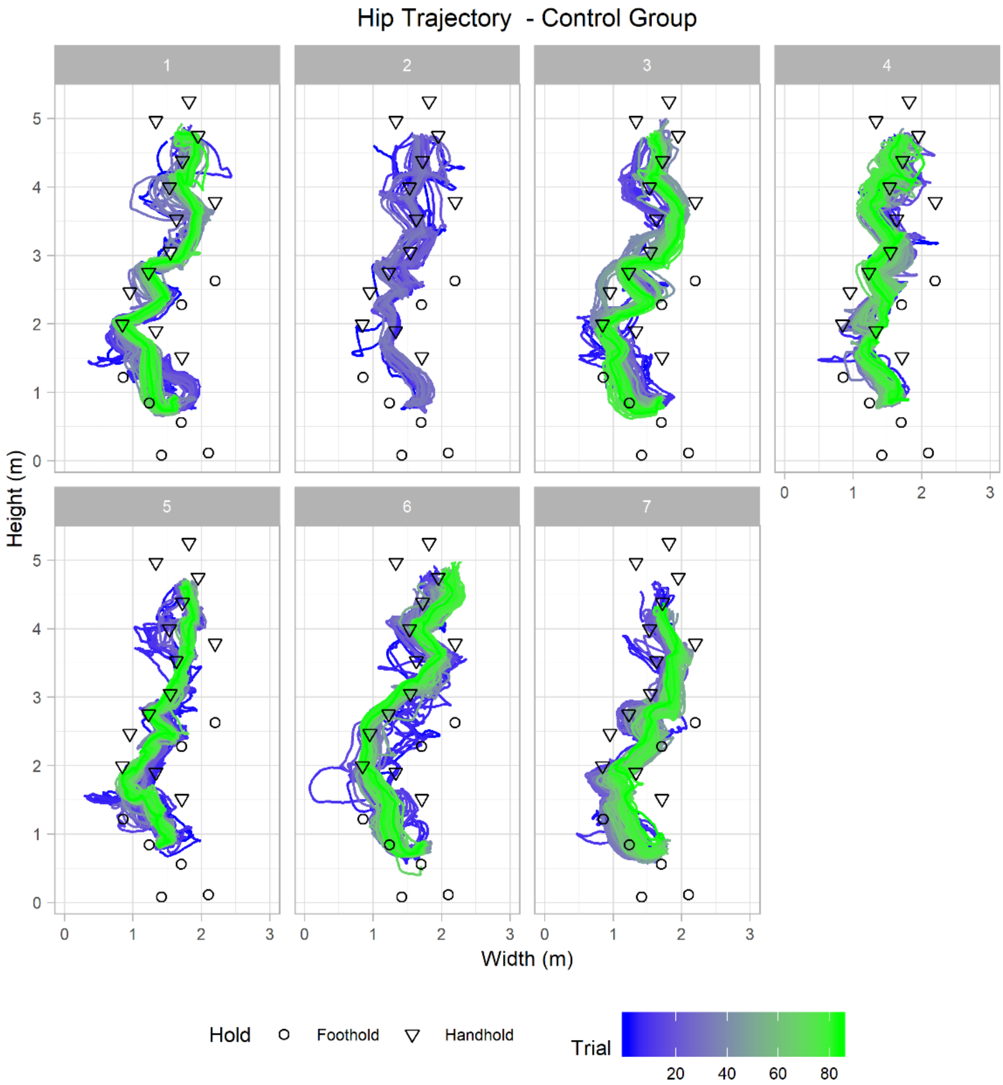

Figure 20. Hip trajectories of the participants of the constant practice group on the control route. Each frame refers to one participant. Dots and triangles refer to the handholds and footholds location on the route.

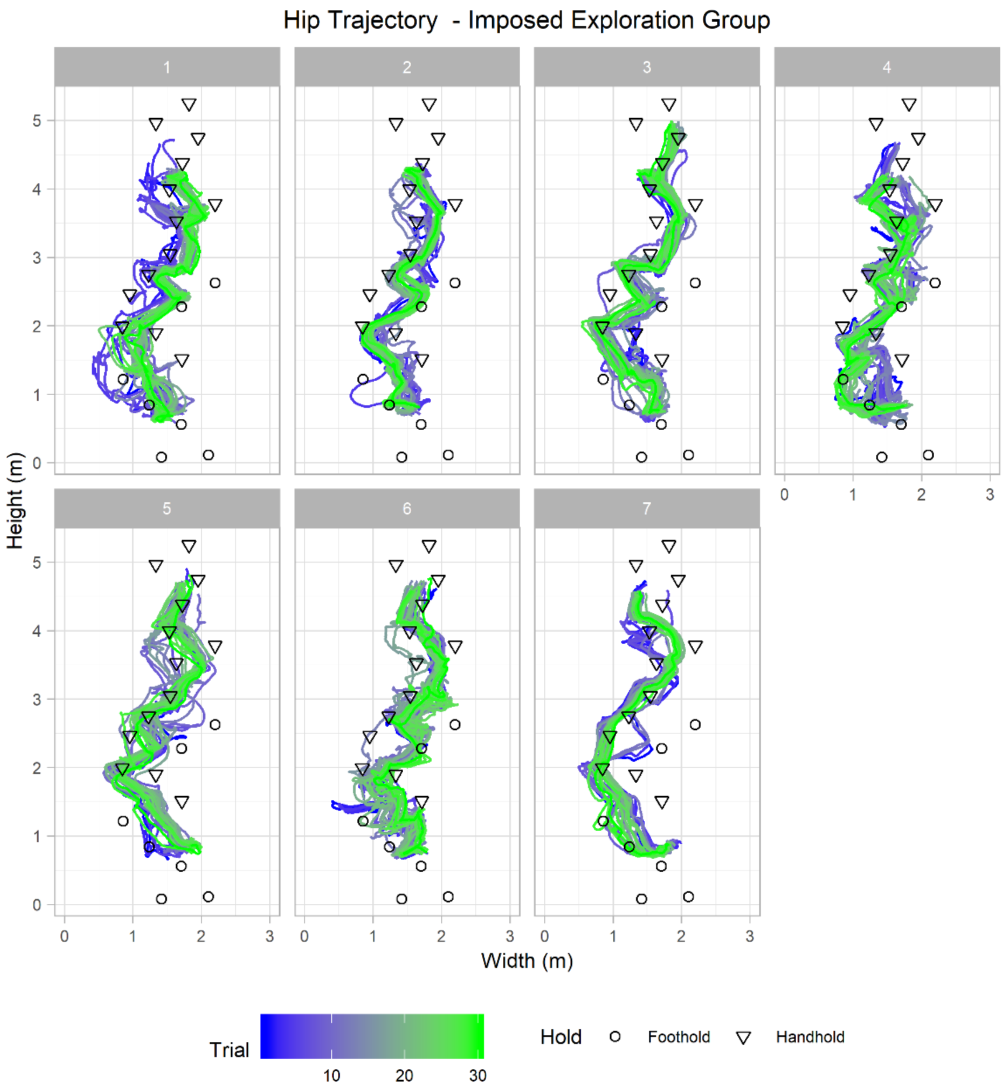

Figure 21. Hip trajectories of the participants of the imposed variability group on the control route. Each frame refers to one participant. Dots and triangles refer to the handholds and footholds location on the route.

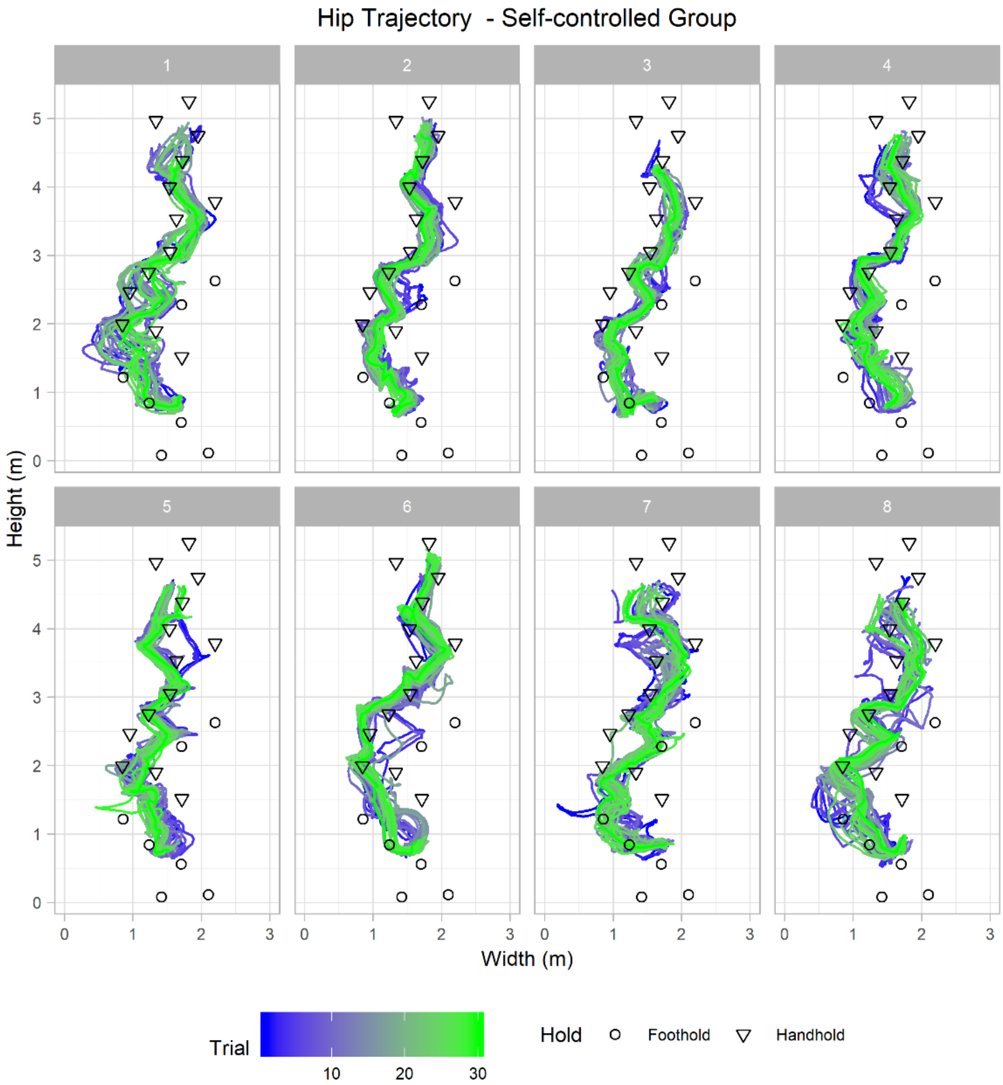

Figure 22. Hip trajectories of the participants of the self-controlled variability group on the control route.
Each frame refers to one participant. Dots and triangles refer to the handholds and footholds location on the route.

Table 20. Individual parameter values and fit of the exponential function.

Participant ID	α	β	λ	R^2
Constant Practice Group				
P1	0.596	0.760	0.181	.599
P2	0.702	0.405	0.204	.333
P3	0.516	0.594	0.060	.673
P5	0.650	1.108	0.071	.902
P6	0.387	0.836	0.067	.862
P7	0.434	0.996	0.057	.850
Imposed Variability Group				
P1	0.626	0.819	0.086	.787
P2	0.535	0.606	0.089	.881
P3	0.687	0.694	0.131	.867
P5	0.457	0.409	0.066	.551
P6	1.002	0.896	0.422	.638
P7	0.420	0.638	0.180	.810
Self-controlled Variability Group				
P1	0.523	0.373	0.100	.505
P2	0.614	0.710	0.138	.859
P3	0.494	0.507	0.109	.847
P4	0.544	0.539	0.181	.736
P6	0.327	0.605	0.037	.643
P7	0.632	0.975	0.154	.833
P8	0.639	0.470	0.106	.738

Table 21. Individual parameter values of the piecewise linear regression.

ID	Group	Slope 1	Slope 2	Breakpoint	R^2
P4	CG	$-3.75*10^{-3}$	$-9.64*10^{-3}$	59	.70
P4	IVG	$\mathbf{-7.47*10^{-3}}$	$-2.76*10^{-2}$	13	.53
P5	SVG	$\mathbf{-8.10*10^{-3}}$	$-1.58*10^{-2}$	16	.58

Note: Bold value indicate that the parameter did not reach significance

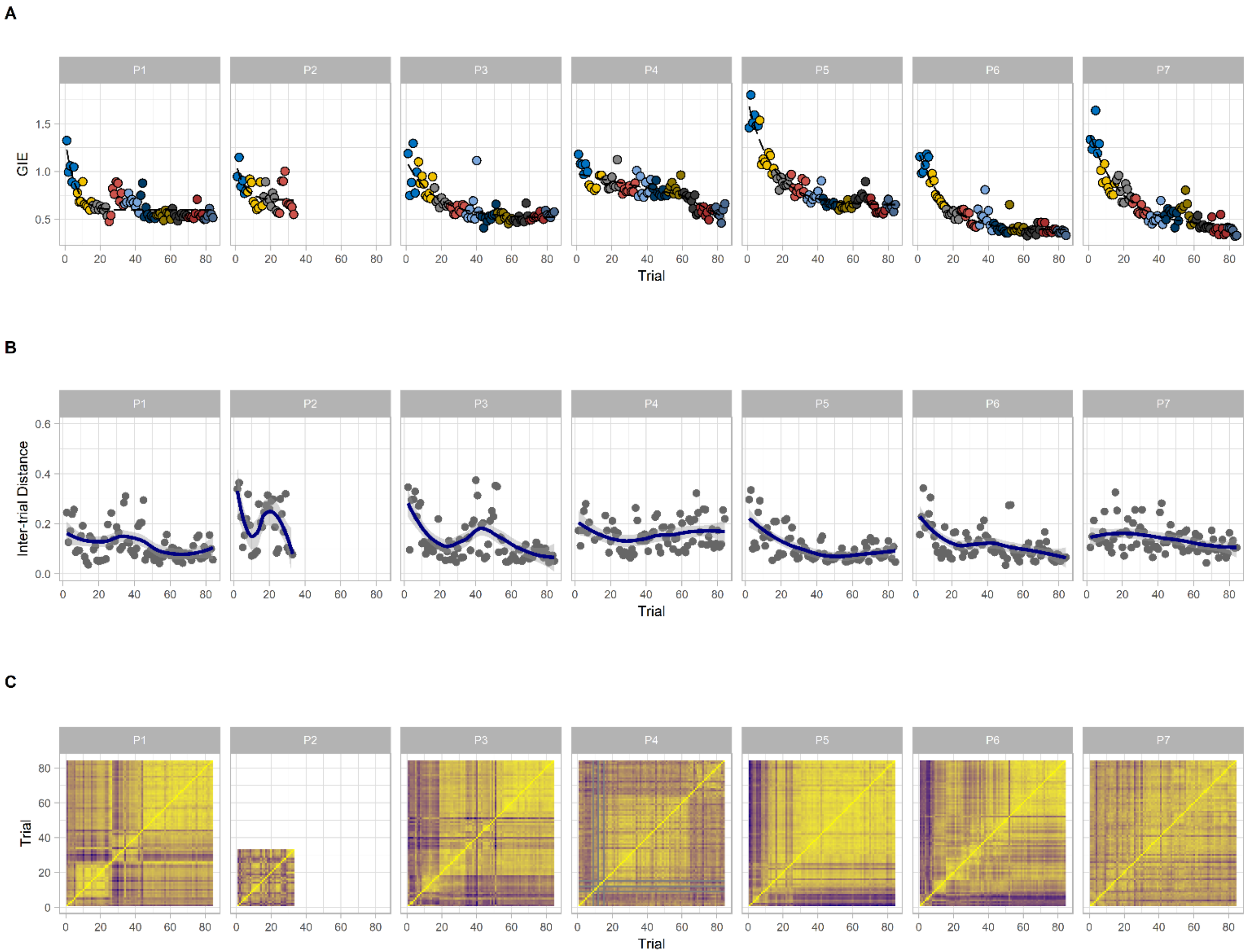

Figure 23. Performance curves (A), inter-trial similarity (B) and matrix of the inter-trial similarity index (C) for each participant of the constant practice group. Each frame corresponds to one participant.

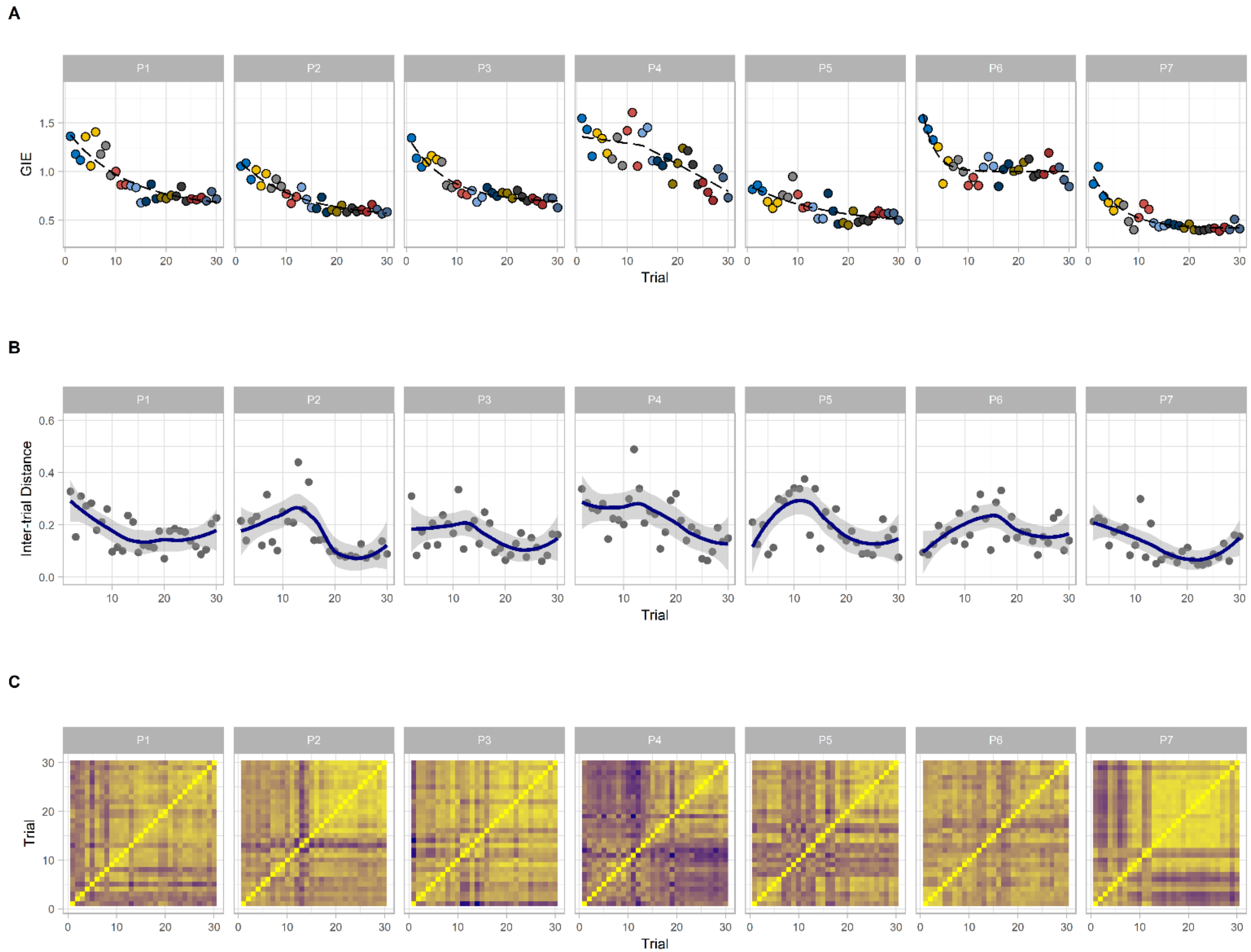

Figure 24. Performance curves (A), inter-trial similarity (B) and matrix of the inter-trial similarity index (C) for each participant of the imposed variability group. Each frame corresponds to one participant.

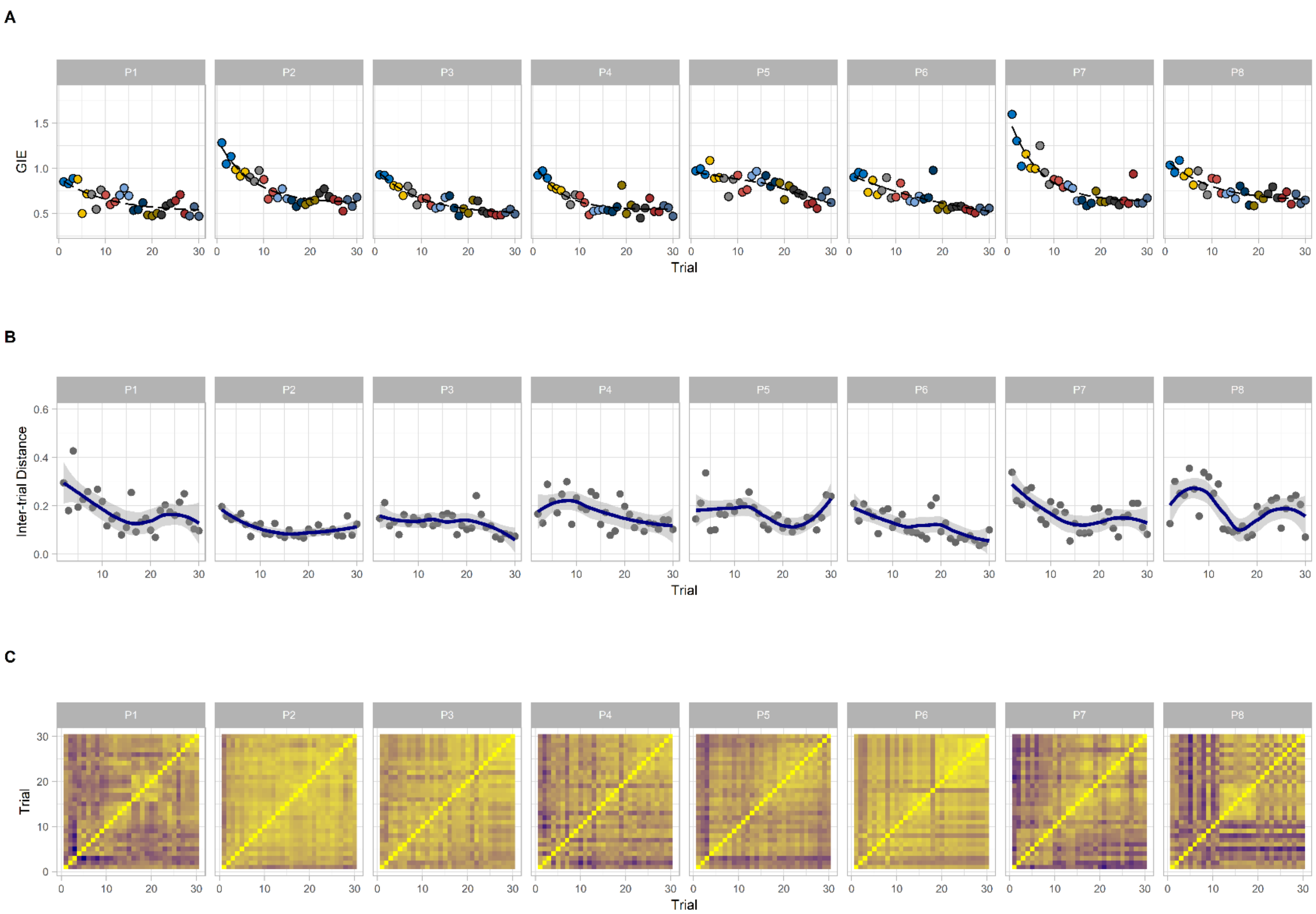

Figure 25. Performance curves (A), inter-trial similarity (B) and matrix of the inter-trial similarity index (C) for each participant of the self-controlled variability group. Each frame corresponds to one participant.

Chapter 7: Variability in Practice Fosters a Proactive Gaze Pattern

Introduction

During the realization of complex everyday skill, gaze behaviors appear to smoothly support movement, but the acquisition of how learners acquire skill-relevant gaze patterns remains an under researched area (Hayhoe & Ballard, 2005; Land & Hayhoe, 2001). Complex situations, such as walking over rough terrain, commonly comprise a series of actions where the visual system is confronted with a dual demand: (i) the accurate control of the current movement; and (ii) the anticipatory search for environmental demands that will constrain future movements (Barton et al., 2019; Land et al., 1999). Studies have revealed a trade-off between the two demands that are modified to adapt to the immediate spatiotemporal conditions (Matthis & Fajen, 2014; Matthis et al., 2018; Yamada et al., 2012). For example, when walking on different terrains, walkers adapt their gaze behavior to the difficulty of the surfaces (Matthis et al., 2018). This adaptation enables walkers to perform accurate foot placement on stable locations and to maintain an efficient locomotion pattern. However, it remains unclear whether different practice conditions can invite learners to acquire gaze patterns that are oriented towards one demand or the other. The current study aims to assess the effects of a constant and two variable practice conditions on the performance and gaze behaviors of learners in climbing to further understand how the visual control of action adapts to different practice conditions and how this may facilitate transfer of learning.

The Timing of Information Pick-up and the Dual demand on Gaze Control

When performing a continuous action in natural settings, the question of when and where to look in order to correctly control movement is of central importance. As information pick-up is dynamic, performers need to attend to the right information at the right time to guide skilled behavior (Oudejans et al., 2005). The performer must find a trade-off between exploiting information for controlling their current movement and monitoring the environment for information that may constrain future movements (Barton et al., 2019; Matthis et al., 2018). Walking across successive foot targets and walking over rough terrain represent paradigms that have been used to better understand how the visual system guides foot placement towards immediate and prospective targets (Barton et al., 2019; Chapman & Hollands, 2006b, 2006a; Yamada et al., 2012). Research across these paradigms show that the spatial demands of stepping accuracy impacts upon gaze behavior: the more accurate the performer’s step needs to be, the more they use online control of their movements (Matthis et al., 2018; Yamada et al., 2012). The constraints are also temporal as the availability of visual information is necessary in critical phases of the step cycle to accurately perform foot placement and to maintain energetically efficient locomotion (Chapman & Hollands, 2006a; Matthis et al., 2017). Although dealing with this dual demand is necessary for everyone, it appears that skill level influences how individuals visually control their actions. For example, older adults who were identified as potential “fallers”, responded to the dual demand when approaching the target with a maladaptive gaze behavior that contributed to their poor stepping accuracy (and potential fall): their gaze shifted towards the next target before their heel had touched the ground in the immediate target (Chapman & Hollands, 2006b). In contrast, younger adults who were not at risk of a fall adopted a gaze pattern that resulted in them looking at the target until heel target (Chapman & Hollands, 2006b). Thus, for precise visual control, it appears important to adopt a gaze pattern that prioritizes the accurate control of the current movement.

There is, however, evidence, which also points to conditions when gaze patterns are oriented towards future environmental conditions. For example, the visual control of movements when avoiding obstacles appears to change during development that coincide with the acquisition of different modes of locomotion (Franchak et al., 2011). For instance, infants that crawl or walk appear to rely more on the online visual guidance of their movements than children and adults who are able to proactively gaze toward obstacles (i.e., they can avoid obstacles while looking elsewhere) (Franchak & Adolph, 2010; Franchak et al., 2011). Regarding the dual demand, the proactive control of movements enables children and adults to anticipate what is coming ahead of them while infants – who are comparatively novices – needed to perform the actions one-by-one utilizing online control. Thus, the dual demand on visual control can be affected by practice with the improvement of motor skills.

In the realization of complex skills, performers are also often constrained by a dual demand. For example, climbers need to control their ongoing movement while looking forward in the route to anticipate future movements. Two studies have investigated the effect of practice on climbers’ gaze behaviors (Button et al., 2018; Hacques, Komar, & Seifert, 2021). The first study showed that after 6 trials, the number of fixations during ascents decreased without affecting the search rate (i.e., the number of fixations divided by the total duration of fixation) (Button et al., 2018). The second study investigated the changes in gaze behaviors of learners before and after performing 30 trials on the same climbing route (over 10 sessions). This study also assessed transfer of learning by using three other routes that differed from the learning route by manipulating some properties of the handholds (i.e., the distances between handholds, their orientation or their shape) (Hacques et al., 2021). The results showed that the "quantity" of exploration (i.e., number of fixations) decreased and the gaze path – as measured by the entropy of the gaze transitions from hold to hold on the route - became less complex with practice. It appeared that gaze entropy was correlated with movement fluency, but only on the routes where the learners were attuned to the shape of the handholds. Taken together, these results suggest that with constant practice conditions, the demand on the anticipation of the future climbing movements decreased. However, the gaze entropy measure did not inform about the timing of the gaze movements relative to the climbing movements, which would reveal how performers deal with the dual demand, either favoring online or proactive gaze control.

Variability in the Practice of Perceptual-Motor Skill

According to learning approaches rooted in dynamical system theory, the ability to transfer learning depends on the variability experienced during practice (Pacheco & Newell, 2015b). These approaches have proposed three different forms of variability in practice: intrinsic variability, unstructured variability, and structured variability (Ranganathan & Newell, 2013). When the same practice condition is repeated, variability in the performed movement has been found to occur from one repetition to the next. This variability, intrinsic to the motor system, is however, insufficient for learners to escape their initial behavioral tendencies. A proposed solution is to add unstructured variability to practice at the level of multiple task parameters (Schöllhorn et al., 2009). This second form of variability aims to provide additional random noise to the learners' movements during practice in order to find the global minimum of the perceptual-motor workspace and escape local minimums where individual intrinsic variability may be insufficient to facilitate learning (Schöllhorn et al., 2009). Thus, it is hypothesized that unstructured variability in practice conditions may increase the learning rate of individuals and improve learning outcomes (i.e., retention and transfer) in comparison with constant practice conditions (Schöllhorn et al., 2009).

Unstructured variability may, however, be counterproductive if learners do not have the opportunity to stabilize the discovered movement patterns and optimize information-movement coupling (Hossner et al., 2016). A third form of practice variability motivated by the ecological approach to perception-action has revealed that the transfer of learning to different conditions occurs when learners attune to information during practice that is also available and reliable in transfer conditions (Huet et al., 2011). In order to guide attunement, variability has been applied to practice conditions so that less useful information becomes unreliable during learning (Fajen & Devaney, 2006). Learners in structured variable practice conditions have been found to attend to more reliable information resulting in better performance in a transfer task than learners in a constant practice group (Huet et al., 2011). Moreover, the learners' attunement and ability to transfer learning differed according to the parameter of the task that was varied during practice (Huet et al., 2011; Smeeton, Huys, et al., 2013), which shows that although variable practice improves generalization, this generalization is specific to the learning conditions.

The rhythm of changes in learning conditions following structured variable practice are usually imposed upon the participants by the experimenters (e.g., Huet et al., 2011). However, studies have shown that even when learners are exposed to the same practice conditions, they demonstrate different learning dynamics (e.g., R. Withagen & van Wermeskerken, 2009). Thus, some participants may not benefit from variable practice if the externally imposed rate of exploration is too great for them to stabilize the newly discovered movement solutions. A proposed solution is to give learners the opportunity to control when to change the practice conditions (e.g., Keetch & Lee, 2007; Liu, Luo, Mayer-Kress, & Newell, 2012; Wu & Magill, 2011). For example, when participants controlled the difficulty of a rollerball task, they were shown to reach a success rate during practice that was better than participants experiencing practice with a progressive increase of difficulty (Y.-T. Liu et al., 2012). Furthermore, participants that were given control of their practice schedule when practicing three sequences of a key-pressing task performed better on a transfer task than participants who had their practice schedules imposed by experimenters (Wu & Magill, 2011). These results also showed that most of the participants chose to start practice using a blocked organization (i.e., with numerous repetitions of one of the tasks before switching to another one) before changing later in practice to become more variable. Thus, by giving control to the participants on the rate at which their learning conditions change, they appear to adapt the changes according to their skill level and their needs in terms of task exploitation. Therefore, learning outcomes in self-controlled practice appear to benefit from a ratio between exploration and exploitation during practice, which are sensitive to individual learning dynamics in comparison to constant practice or an imposed structured variable practice (Y.-T. Liu et al., 2012; Wu & Magill, 2011).

In existing research, intrinsic variability and unstructured variability in practice have primarily been investigated using discrete multiarticular tasks (e.g., Hung, Kaminski, Fineman, Monroe, & Gentile, 2008; Schöllhorn et al., 2006). In contrast, structured variable practice was shown to improve the transfer of learning for a discrete anticipation task (Smeeton, Huys, et al., 2013) and in continuous tasks where learners had to adapt their actions to the unfolding dynamics of the task (Fajen & Devaney, 2006; Huet et al., 2011). The perceptual-motor tasks used in these structured variable practice studies were performed in virtual environments to facilitate the control (and variations) of the available information. However, the transfer of the findings to natural settings may not be straightforward. First, the possible movements of learners are restricted during virtual environments. Second, virtual environments may lead to the attunement to information, which may be detrimental for the transfer of learning from virtual environments to natural settings (Goodale, 2017; Harris, Buckingham, Wilson, & Vine, 2019). In sum, the available information in natural settings is more complex, and the movements usually involve more degrees of freedom, which gives learners a greater variety of opportunities to explore (i.e., to pick up information) through their actions.

Present Experiment

Literature demonstrates that variability during practice may guide learning and help to develop more adaptive perceptual-motor behaviors in comparison to constant practice (Huet et al., 2011). However, it remains unclear how different practice conditions affect the learners' gaze behavior and whether the change in gaze behavior is related to the learning outcomes. To address this gap, the aims of the current study were therefore (i) to investigate the effect of different types of practice on how learners deal with the dual demand on their gaze behavior, and (ii) to analyze the extent that this effect may be associated with the transfer of learning to a new climbing route.

In the current study, we compared the changes in performance and gaze behavior of participants in a constant practice condition (Constant group, CG) to a group in a structured variable practice condition (Imposed Variability group, IVG) on a training route, and we assessed the transfer of learning to a new route (i.e., the transfer route). We expected that, with practice, the learners in the two groups would differently balance the dual demand of gaze behavior. We expected that the IVG would demonstrate more proactive gaze behaviors than the CG on both the training and transfer routes. These differences would enable the IVG to adopt a gaze behavior that is better adapted to climbing a new route as it would enable them to have a more proactive control of their climbing movements. Conversely, the gaze behavior developed by the CG on the training route may not be best adapted to climbing a new route as learning may be attuned to the training route, where continual exploration will likely reduce after extended practice in the same learning environment. Second, we examined whether giving the participants the opportunity to control when to be confronted to a new climbing route (Self-controlled Variability group, SVG) would improve learning, and transfer of learning, in comparison to the group with an imposed schedule of climbing routes (the IVG). We expected that participants in SVG would benefit from learning to control the optimal ratio between exploration and exploitation during practice, which would result in better performance on the training and transfer routes. This optimal ratio would also translate into a gaze behavior that is less proactive than the IVG on both routes, suggesting a heightened skill in coupling information to movements.

Method

Participants

Twenty-four undergraduate students who volunteered to take part in the study were recruited (age: *M* = 20.6 years, *SD* = 1.1; 8 women and 16 men). Sample sizes were driven by the availability of participants (i.e., students able to attend to two learning sessions per week for 5 weeks) and previous work in this area (perceptual-motor learning in climbing; e.g., Button et al., 2018; Orth, Davids, & Seifert, 2018; Seifert et al., 2018). Their skill level was in the lower grade group according to the International Rock Climbing Research Association scale (Draper et al., 2015) as they had no or very little climbing experience. They all had normal or corrected to normal vision. Participants were randomly assigned to the CG, the IVG and the SVG. Before the first climbing session, the protocol was explained to all the participants, who then provided written informed consent to participate in this study. The protocol was approved by the Institutional Review Board of the local university ethics committee and the French National Agency of Research (ID: ANR-17-CE38-0006 DynACEV) in accordance with the Declaration of Helsinki.

Experimental Design

Learning protocols

Participants attended 10 learning sessions that lasted for 5 weeks, with 2 sessions per week. The participants in the CG always climbed the same route, called the *training route* (84 trials in total). The participants in the IVG practiced on the *training route* (learning session 1) and on nine subsequent variations of the training route (the *variant routes*). Thus, the IVG practiced on a new variation of the training route in each session. The SVG followed the same protocol as the IVG with the difference that at the end of sessions 2 to 9, they were asked whether they wanted to continue practicing on the same route or if they wanted to change the route on which they performed the highest number trials. Thus, they could follow the same protocol as the IVG if they always chose to change the route. The content of the sessions is summarized in **Table 22**.

Table 22. Program of the learning sessions for the three groups.

	Constant Group	Imposed Variability Group	Self-controlled Variability Group
Session 1	**1xTransfer | 3xTR |** 3xTR	**1xTransfer | 3xTR** | 3xV1	**1xTransfer | 3xTR** | 3xV1
Session 2	9xTR	3xTR | 3xV1 | 3xV2	3xTR | 3xV1 | 3xV2
Session 3	9xTR	3xTR | 3xV2 | 3xV3	3xTR | 3xV? | 3xV?
Session 4	9xTR	3xTR | 3xV3 | 3xV4	3xTR | 3xV? | 3xV?
Session 5	9xTR	3xTR | 3xV4 | 3xV5	3xTR | 3xV? | 3xV?
Session 6	9xTR	3xTR | 3xV5 | 3xV6	3xTR | 3xV? | 3xV?
Session 7	9xTR	3xTR | 3xV6 | 3xV7	3xTR | 3xV? | 3xV?
Session 8	9xTR	3xTR | 3xV7 | 3xV8	3xTR | 3xV? | 3xV?
Session 9	9xTR	3xTR | 3xV8 | 3xV9	3xTR | 3xV? | 3xV?
Session 10	**3xTR |** 3xTR **| 1xTransfer**	**3xTR** | 3xV9 | **1xTransfer**	**3xTR** | 3xV? | **1xTransfer**

Note: The table presents the content of each learning session for the three practice conditions. On the first and last session, the participants climbed a transfer route (Transfer). The participants in the Constant group climbed a training route (TR) 6 to 9 times per session. The participants in the Imposed Variability group climbed the training route 3 times on all the sessions and they climbed 9 variants routes (V1 to V9) across the learning protocol. The Self-controlled Variability group followed a similar protocol as the Imposed Variability group, but the number of variants routes discovered depended on the individuals' choice during the practice. The data collected from the trials written in bold characters are those analyzed in the current study.

Transfer Test

The transfer test consisted of two trials on a climbing route called *Transfer route*. The first trial was performed at the beginning of the first learning session and was used as a baseline. The second trial was performed after the last trial of the last learning session to examine the effect of the three learning protocols on the transfer of learning.

Route Design

The experiment took place in a climbing gym where two walls were used: the first was used for the training route and the second for the transfer route and the variants. Two routes could be placed on the second wall. Each route was hidden with a tarpaulin so that participants could only see the route to be climbed. All routes were designed with the same two models of climbing holds (Volx Holds®, Chessy-les-mines, France): one for handholds and one for footholds. The variants were designed with the same number of holds as the training route (i.e., 13 handholds and 7 footholds) and the transfer route was composed of 13 handholds and 6 footholds, but the layout of the holds on the wall differed between routes. The training route was 525 cm high, and the other routes were 480 cm high.

Instruction

The participants were prompted on each trial of the learning sessions (i) to climb as fluently as possible, avoiding pauses and saccadic movements of the body, (ii) to use all the handholds in an order from the bottom-top of the wall, and (iii) to use all the handholds and footholds with a single limb contact at a time (participants couldn't use a hold with both hands or feet at once). The instructions were repeated before each trial. These prompts were given so that the problem that participants had to solve was to find the most efficient chain of movements to reach the top of the climbing route. Specifically, this problem relates to what has been called route-finding skill in climbing (Sanchez, Lambert, Jones, & Llewellyn, 2012).

Procedure

In total, each session lasted approximately 1 h. Therefore, the entire study comprised a total of 240 hours, when accounting for the testing and practice of all participants. Each session started with a 10 min warm-up in a bouldering area. The participant was equipped with climbing shoes, a harness and the mobile eye-tracker and was told the instructions. On the first session, one of the experimenters demonstrated how to climb in a bouldering area in accordance with the instructional prompts and invited the participants to try. Then, the participant warmed-up while familiarizing with the prompts in the bouldering area.

Then, the same procedure was performed for each trial: (i) the route to be climbed was uncovered, the others were hidden with a tarpaulin, (ii) the mobile eye tracker was calibrated, and the recording started, (iii) the participant stood 3m in front of the route for 30s of route preview. The participant could stop the preview when they wanted. During the preview, the experimenters started the video recording. (iv) The participants were top roped, that is, the rope was anchored at the top of the wall and to the participant for security during the ascents. (v) The prompts were provided by the experimenter to the participant. (vi) The experimenter then performed the synchronization procedure (see Synchronization Procedure). (vii) The participants were placed in the starting position, holding the first handhold with two hands and their feet were on the first two footholds. (viii) When the participants were ready and secured, the experimenter announced that they could start the climb. The climbed ended when the participants grasped the last handholds and remained immobile for a few seconds. (ix) The participant was then lowered down, and all the recordings were stopped.

Data Collection

Contact Time with Holds

The climbing walls were equipped with the Luxov Touch ® system (http://www.luxov-connect.com/en/products/#touch, Arnas, France) as already used recently by Seifert, Hacques, Rivet, & Legreneur (2020). This system uses a capacitive sensing technology to provide a measure of the time of contact and release of the handholds and footholds (**Appendix A**, **Figure 36**). The reported accuracy of the system is 1.57 ms at 99.7% confidence interval (see patent details: FR3066398-2018-11-23 / WO2018/211062A1-2018-11-22; https://patents.google.com/patent/WO2018211062A1/en).

The starting time and ending time of the climb were obtained with this system. The start time was considered when the participant touched another hold other than the starting holds and the end of the climb was considered when the climber touched the last handhold. The time of the first contact with each of the handholds of the routes were also collected.

Tracking of the Hip Trajectory

Trials were filmed at 29.97 fps on 1920x1080 pixels frames with two GoPro 5 cameras (GoPro Inc. ®, San Mateo, CA, USA), each camera captured an entire wall. The cameras were placed at a height of 2.80m. On the back of the participants' harness, a light was placed.

The videos of the cameras were imported in Kinovea© (version 0.8.25, Boston, MA, USA). The lens distortion was corrected by importing the intrinsic parameters of the cameras lens in Kinovea from Agisoft lens (version 0.4.1, Agisoft LLC, Saint Petersburg, Russia). A manually set grid was used to correct the perspective and to calibrate the distances by using markers placed on the climbing routes. The light on the back of the participant was tracked from the reference frame (when the experimenter tapped the hold) until the moment the climber touched the last handhold of the route. The tracking was used to get the projected coordinates of the hip position on the 2D wall for each frame of the video. The starting and ending times obtained from the Luxov Touch system were used to cut the temporal series of the hip position to have the fluency measure corresponding to the climbing period.

Gaze Behavior

The climber wore mobile eye-tracking glasses (Tobii Pro Glasses 2©, TobiiAB®, Sweden) on each trial. The glasses tracked the eye movements at a frequency of 50Hz with two cameras under each eye which after calibration, provided the gaze location on the video scene camera placed between the two eyes on the front of the glasses that recorded at 25fps on 1920x1080 pixels frames. Before each trial, the calibration was done by placing a target at an arm's length from the standing participant. After the calibration, the accuracy of the gaze location was then checked by asking the participant to look again at the target. If the calibration failed or the point of gaze did not overlap with the target, the procedure was repeated until that the gaze location was considered sufficiently accurate.

Synchronization Procedure

The data from the mobile eye-tracker and the Luxov Touch system were synchronized by asking the participant to look at one hold while the experimenter tapped on it. Then the time of the first frame in the video of the eye tracker that showed the contact of the experimenter's finger with the hold was used as a reference time to synchronize the two. This synchronization was used to obtain the gaze offset time (see in the subsection Gaze Behavior within the section Data Analysis for more details and reliability measures regarding this dependent variable).

Data Analysis

Climbing Fluency

The coordinates of the hip trajectory were used to compute the geometric index of entropy (GIE). The GIE was designed as a measure of performance that reflects the degree of coherence in information-movement couplings (Cordier, Mendés France, et al., 1994). The GIE enables assessment of the degree of complexity of the hip trajectory. A complex hip trajectory would reflect a poor sensitivity of the climber to the environmental constraints, whereas a smooth trajectory would reflect fluent climbing movements. GIE is calculated with the following equation:

$$GIE = \log_2(\frac{2L}{c})$$

L is the length of the hip trajectory and c the perimeter of the convex hull around the hip trajectory. Data analyses to obtain the GIE values were performed with Matlab R2014a ® software (version 8.3.0.532, The MathWorks Inc., Natick, MA, USA).

Gaze Behavior

This experiment focused on the gaze behavior related to the handholds and hand movements of the participants. The analyses of the mobile eye tracker recordings were performed using Tobii Pro Lab© (version 1.102.16417, TobiiAB, Sweden). The raw filter was applied to provide data on the location of the gaze position on each frame. A circle with a 20 cm radius around each of the 13 handholds was considered as areas of interest (AOI). Two different aspects of gaze behavior were coded for each ascent: (i) the last period the participant's gaze stayed within an AOI before touching the corresponding handhold for the first time in the trial, and (ii) the temporal series of the AOI that the point of gaze passed through.

For the first measure, the coder recorded the last period that the participant's point of gaze stayed within an AOI before touching the corresponding handhold for the first time in the trial (Chapman & Hollands, 2006b). This was repeated for each handhold of the route with the exception of the starting handhold and last handhold (N = 11). Subsequently, the onset and offset time of each gaze period that related to these periods of gaze within an AOI before contact were recorded. If the onset or offset time could not be collected due to missing gaze samples, the entire period was not considered for analysis. The gaze onset and offset times were related to the contact time of the handhold given by the Luxov Touch system. Thus, the visits with a negative offset time would correspond to a proactive control of the hand movement, as the participant's gaze would have move away from the AOI before the moment of contact with the handhold. Using the offset time, we calculated the proportion of online visits, that is, the proportion of visits with a positive offset time, meaning that participant's gaze was within the AOI at the moment of contact with the handhold. The duration of the gaze visit was also obtained from onset and offset time.

For the second measure, to be considered in the temporal series, the point of gaze needed to remain within the AOI of the handhold for more than 3 frames (i.e., 60ms), otherwise, it would be considered as an eye movement passing by the AOI and thus would not be coded. Also, the handhold should be either one of the currently grasped by the participant, or one above them, so that the results only inform about the gaze displacements relating to the current or next hand movement of the performer.

The temporal series of visited AOIs was used to calculate the conditional visual entropy measure. The conditional visual entropy (H) was calculated with the following equation (Ellis & Stark, 1986):

$$H = -\sum_{i=1}^{n} p(i)\left[\sum_{j=1}^{n} p(i,j)\log_2 p(i,j)\right], i \neq j$$

with p(i) the probability of visiting the AOI i, and p(i,j), the probability that the gaze shift from i to j. The higher the value of the conditional visual entropy, the more the gaze path went from an AOI to another in a random manner whereas a low value would reflect a structured gaze path (Shiferaw et al., 2019). It should be noted that, if the participants gaze shifted from one AOI to the next on the ascent, the value of H would be 0 as all p(i,j) would be 1. We expected that with practice, participants conditional visual entropy would tend to 0.

The reliability of the coding method was assessed on eight trials taken randomly. This sample was coded a second time by the original coder two months after the first coding and by a second researcher. For the three dependent variables relating to gaze behaviors, we performed Pearson correlations that showed that the intra-coder reliability ranged between r = .994 and r = .997 and the inter-coder reliability between r = .991 and r = .993. For the measure of the gaze offset time (which could be affected by the synchronization procedure), the intra-coder mean difference between the first and second coding was -0.9ms (*Mean 95% CI = [*-4.1ms, 2.3ms*], SD = 14.6ms*) and the inter-coders mean differences was -0.2ms (*Mean 95% CI = [*-3.8ms, 3.4ms*], SD = 16.3ms*).

Global Observations Regarding the Gaze Sample. The gaze behavior of one participant in the IVG was excluded from the analysis due to the loss of gaze data during the climbs. For the rest of the participants, the offset time and duration of the period of gaze within AOI was obtained for 91.3% of the visits on the training route and for 86.6% of the visits on the transfer route. There was no significant difference in the proportion of excluded periods in the three learning groups on the training route [$\chi2(2, N = 1205) = 0.98$, $p = .612$] and on the transfer route [$\chi2(2, N = 381) = 0.66$, $p = .719$].

Statistical Analysis

The dependent variables were submitted to separate mixed ANOVA with Session (2) as a within participant factor and Group (3) as a between participant factor. The Levene tests for homogeneity of variance and Shapiro-Wilk tests for normal distribution were performed before running the mixed ANOVA. If the tests were significant for GIE or conditional visual entropy, outliers were (i) identified with the identify_outliers() function from the rstatix package (Kassambara, 2020; R Core Team, 2019), and (ii) replaced by the mean of the corresponding series and the tests were performed a second time. For the offset times and durations of the gaze visits, if the tests were significant, outliers were removed, and the tests were performed a second time. In the event of nonsignificant results in the mixed ANOVA, we also performed Bayesian mixed ANOVA and reported the Bayes factors (*BF*) to assess the evidence in favor of the null or the alternative hypothesis (Dienes, 2014, 2016). The mixed ANOVA was followed by post-hoc tests with a Bonferroni correction of the *p*-value to examine the main factors Session and Group. In case of significant result regarding the interaction between Session and Group, planned contrast tests were used to examine the practice effect for each group, and to assess whether this practice effect was different between groups. The generalized eta squared (η_G^2) is reported as a measure of effect size with values of .02 as small, .13 as medium and .26 as large effect (Bakeman, 2005). All the statistical analyses were run using JASP (JASP Team, 2020).

Results

Two participants only attended the first session and then dropped out and one participant injured herself after the fourth training session and could not continue the protocol. Thus, these three participants were removed from the statistical analyses.

Practice Schedule of the SVG

The self-controlled scheduling of the practice condition for participants in the SVG are displayed in the **Table 23**. All the participants chose at least once to practice on the same variants in the following session, thus none of the participants of the SVG followed the same practice schedule as the IVG. Although the participants were, in general, likely to change the variants, the proportion of participants who chose to keep the same variants increased on the two last sessions, with the proportion of change decreasing to .50 in the last session.

Table 23. Practice schedule of the participants in the SVG.
Grey frames show when participants chose to maintain the same variants on the following session, whereas white frames display when they chose to practice on a new variant. The proportion of change is the proportion of participants who chose on each session to practice a new variant route on the following session.

Participant	Session							
	2	3	4	5	6	7	8	9
P1								
P2								
P3								
P4								
P5								
P6								
P7								
P8								
Proportion of change	.875	.875	.750	.875	.750	.750	.625	.500

Changes in Climbing Fluency and Gaze Behaviors on the Training Route

Climbing Fluency

Figure 26 displays the GIE scores of the participants. The mixed ANOVA applied to the GIE showed a large effect of the factor Sessions [$F(1,18) = 275.73$, $p < .001$, $\eta_G^2 = .72$], and a small effect of the interaction between the main factors of Session and Group [$F(2,18) = 6.38$, $p = .008$, $\eta_G^2 = .11$], whereas the Group effect was not significant [$F(2,18) = 1.00$, $p = .389$, $\eta_G^2 = .08$]. The results of the Bayesian mixed ANOVA suggested anecdotal evidence in favor of a Group effect (*BF* = 2.17). The contrast tests revealed that participants across all three groups had more complex hip trajectories in session 1 than session 10 (*M* = -0.51, *CI* = [-0.58, -0.45], *ps* < .001). This change in the spatial fluency score with practice was significantly higher for CG than for IVG (*M* = -0.11, *CI* = [-0.20, -0.03], *p* = .009) but no significant difference was observed between the IVG and the SVG (*M* = -0.01, *CI* = [-0.09, 0.07], *p* = .762).

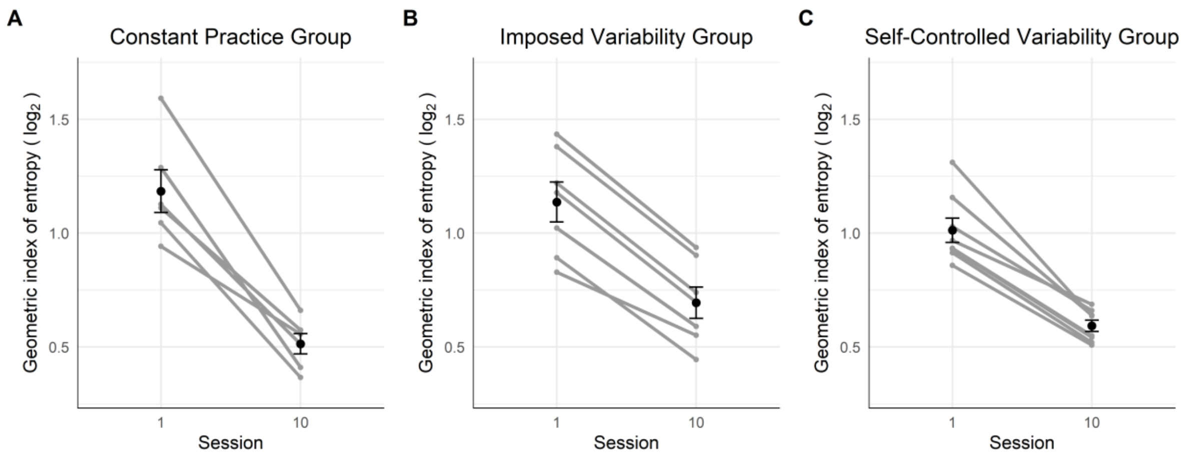

Figure 26. Climbing fluency on the training route.
Dynamics of the climbing fluency on the first and last session of the protocol for the three groups. The black points represent the sessions mean and the error bars their standard error. The grey points and lines represent each participant's dynamics.

Complexity of the Gaze Path

Regarding the measure of the complexity of the gaze path, we performed the mixed ANOVA although the data on the session 10 were not normally distributed due to repeated values in the CG (n = 3).

Figure 27 displays the visual entropy scores of the participants. The mixed ANOVA showed a large effect of the factor Session [$F(1,15) = 93.06$, $p < .001$, $\eta_G^2 = .74$] but no significant effect of the factor Group [$F(2,15) = 1.52$, $p = .250$, $\eta_G^2 = .10$] and the interaction between Session and Group [$F(2,15) = 1.50$, $p = .255$, $\eta_G^2 = .08$]. The Bayesian mixed ANOVA suggested anecdotal evidence in favor of the null hypothesis for the factor Group (BF = 0.58), and anecdotal evidence in favor of an effect of the interaction between Session and Group (BF = 1.03). The post-hoc test revealed that participants' gaze showed less variability in session 10 compared to session 1 (M = -0.38, CI = [-0.47, -0.30], $p < .001$).

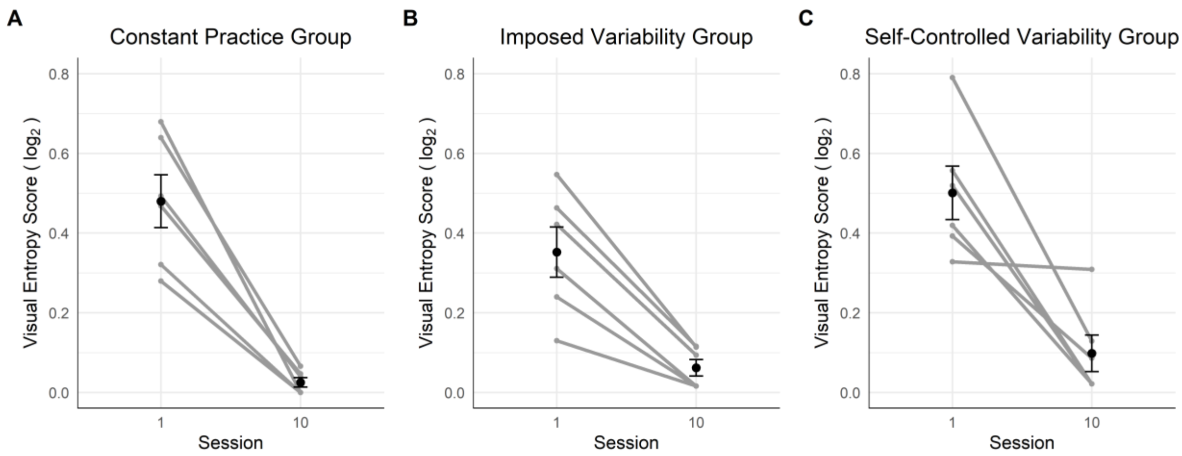

Figure 27. Visual entropy on the training route.
Dynamics of the visual entropy score on the first and last session for the three groups. The black points represent the sessions mean and the error bars their standard error. The grey points and lines represent each participant's dynamics.

Characteristics of the Last Gaze Visit

Offset Time. Figure 28 displays the offset times of the last gaze visits on handholds before touching them. The results of the mixed ANOVA showed a medium effect of the interaction between Session and Group on the visit offset time [$F(2,17) = 7.14$, $p = .006$, $\eta_G^2 = .16$], whereas the main factor Session [$F(1,17) = 0.18$, $p = .68$, $\eta_G^2 = .00$] and Group [$F(2,17) = 2.37$, $p = .124$, $\eta_G^2 = .18$] were not significant. The Bayesian mixed ANOVA suggests anecdotal evidence in favor of an effect of the main factors Session (*BF* = 1.35) and Group (*BF* = 2.29).

The contrast tests showed that the change in the visit offset time with practice was different between CG and IVG (*M* = +68ms, *CI* = [+30 ms, +106 ms], *p* = .001) as the CG visit offset time occurred later on session 10 than on session 1 (*M* = +74 ms, *CI* = [+20 ms, +128 ms], *p* = .010) whereas practice had an opposite effect on IVG as the visit offset time occurred earlier on session 10 than on session 1 (*M* = -62 ms, *CI* = [-116 ms, -8 ms], *p* = .026). The change in the visit offset time with practice was not significantly different between IVG and SVG (*M* = -34 ms, *CI* = [-70 ms, +2 ms], *p* = .060), although practice did not significantly affect the visit offset time of SVG (*M* = +6 ms, *CI* = [-41 ms, +52 ms], *p* = .798).

For the CG, the proportion of online visits increased between session 1 and 10, from .40 to .68 [χ^2 (1, N = 380) = 29.75, $p < .001$] (**Figure 28D**). Conversely, the proportion of online visits decreased between the two sessions for the IVG, from .44 to .27 [χ^2 (1, N = 364) = 11.54, $p < .001$] (**Figure 28E**). For the SVG, the proportion of online visits did not change significantly [.41, χ^2 (1, N = 461) = 1.87, $p = .171$] (**Figure 28F**). Thus, while the CG appeared to favor online control of hand movements with practice, the IVG tended to adopt a proactive control of hand movements.

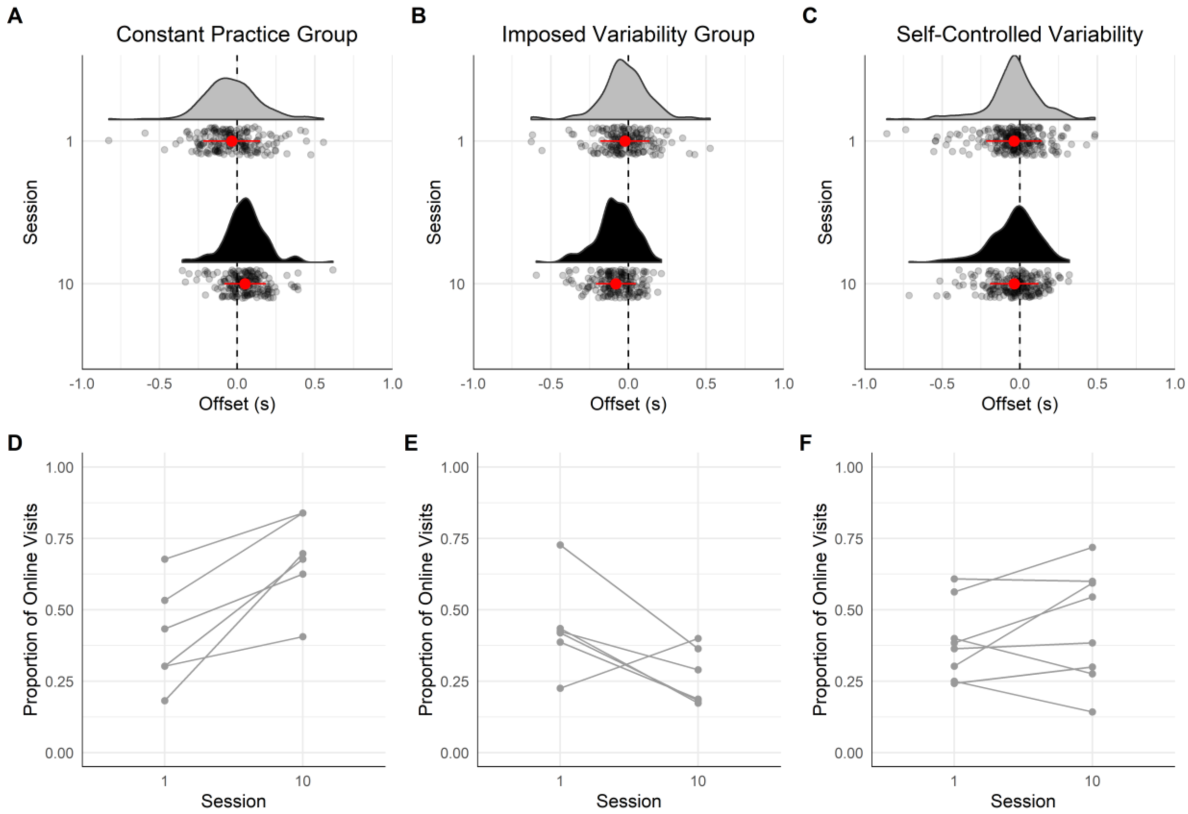

Figure 28. Offset time on the training route.
Offset time of the last gaze visit before the hand contacted the handhold for the three groups on the training route. In panels A, B and C, the vertical dashed line shows the time the hand touched the handhold, each point represents one gaze visit, the half violin shows the density of points, the red/grey point with the error bar refers the mean of all the gaze visits and the standard deviation around the mean. The color of the half violin refers to the learning session: in grey, session 1 and in black, session 10. Panels D, E and F displays the individuals' proportion of online visits on session 1 and 10. Panels A and D show data for the constant practice group, panels B and E for the imposed variability group, and panels C and F for the self-controlled variability group.

Gaze Duration. Figure 29 displays the duration of the last gaze visit on handholds before touching them. The mixed ANOVA revealed a large effect of the main factor Session [$F(1,17) = 46.50$, $p < .001$, $\eta_G^2 = .49$] and no significant effect for the main factor Group [$F(2,17) = 0.99$, $p = .394$, $\eta_G^2 = .07$] and the interaction between Session and Group [$F(2,17) = 1.54$, $p = .242$, $\eta_G^2 = .06$]. The Bayesian mixed ANOVA suggested anecdotal evidence for the null hypothesis regarding the main factor Group (*BF* = 0.50) and the interaction between Session and Group (*BF* = 0.81). The post-hoc test showed that the duration of the visit was significantly shorter in session 10 in comparison to session 1 (*M* = -122 ms, *CI* = [-160 ms, -85 ms]), $p < .001$).

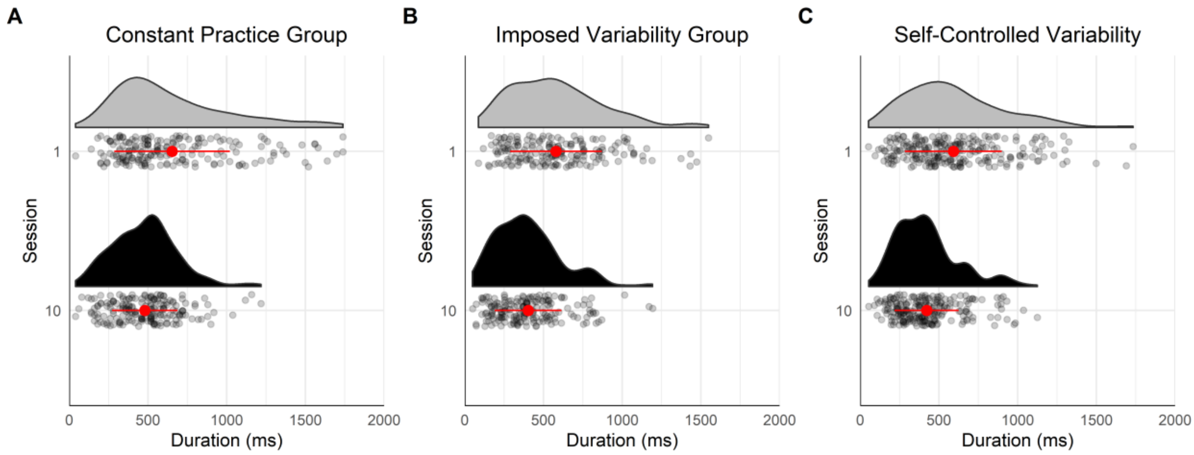

Figure 29. Duration of the last gaze visit on the training route.
Duration of the last gaze visit before the hand contacted the handhold for the three groups on the training route. In panels A, B and C, each point represents one gaze visit before a contact with a handhold, the half violin shows the density of points, the red/grey point with the error bar refers to the mean of all the gaze visits and the standard deviation around the mean. The color of the half violin refers to the learning session: in grey, session 1 and in black, session 10. Panels A, B and C shows data for the constant practice group, imposed variability group and the self-controlled variability group respectively.

Changes in Climbing Fluency and Gaze Behaviors on the Transfer Route

Climbing Fluency

The Levene test showed that the assumption of equality of variances was violated on session 1 [$F(2,18) = 6.36$, $p = .008$]. The mixed ANOVA applied to the GIE revealed a large effect of the main factor Session [$F(1,18) = 42.38$, $p < .001$, $\eta_G^2 = .43$] but no significant effect for the factor Group [$F(1,18) = 2.06$, $p = .157$, $\eta_G^2 = .13$] and the interaction between Session and Group [$F(2,18) = 0.39$, $p = .685$, $\eta_G^2 = .01$]. The Bayesian mixed ANOVA suggested anecdotal evidence for the null hypothesis regarding the main factor Group (*BF* = 0.77) and the interaction between Session and Group (*BF* = 0.62). The post-hoc test showed that the hip trajectory of the participants was significantly less complex in session 10 in comparison to session 1 on the transfer route (*M* = -0.42, *CI* = [-0.55, -0.28]), *p* < .001) (**Figure 30**).

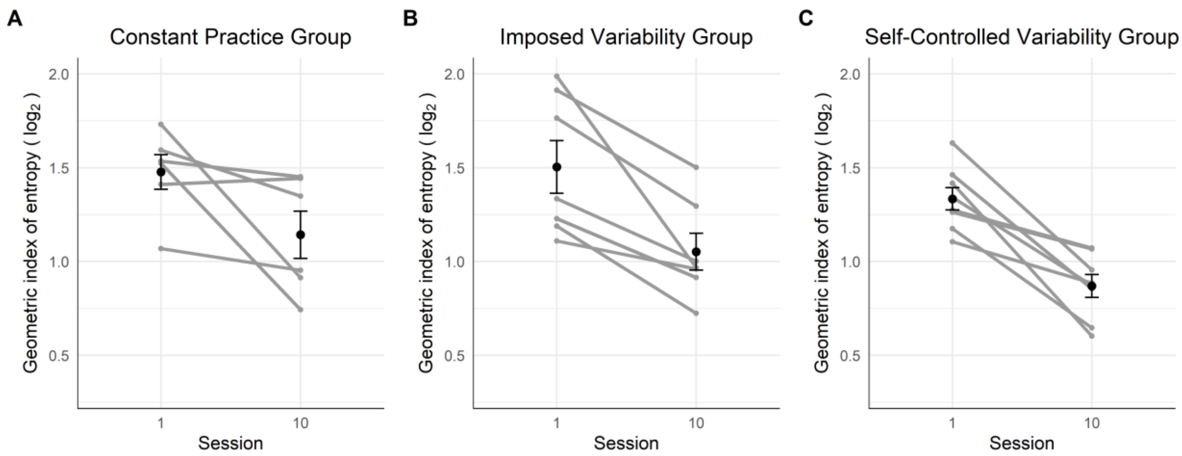

Figure 30. Climbing fluency on the transfer route.
Changes in the climbing fluency of the three groups on the transfer route. The black points represent the sessions mean and the error bars their standard error. The grey points and lines represent each participant's dynamics.

Complexity of the Gaze Path

The mixed ANOVA applied to the visual entropy scores revealed a large effect of the main factor Session [$F(1,15) = 58.35$, $p < .001$, $\eta_p^2 = .60$] whereas the main factor Group [$F(2,15) = 0.22$, $p = .809$, $\eta_p^2 = .02$] and the interaction between Session and Group [$F(2,15) = 0.74$, $p = .495$, $\eta_G^2 = .04$] were not significant. The mixed Bayesian ANOVA suggested medium and anecdotal evidence in favor of the null hypothesis for the factor Group (*BF* = 0.30) and the interaction between Session and Group (*BF* = 0.44) respectively. The contrast test showed that the variability of the gaze path decreased on session 10 (*M* = -0.40, *CI* = [-0.51, -0.29], *p* < .001) (**Figure 31**).

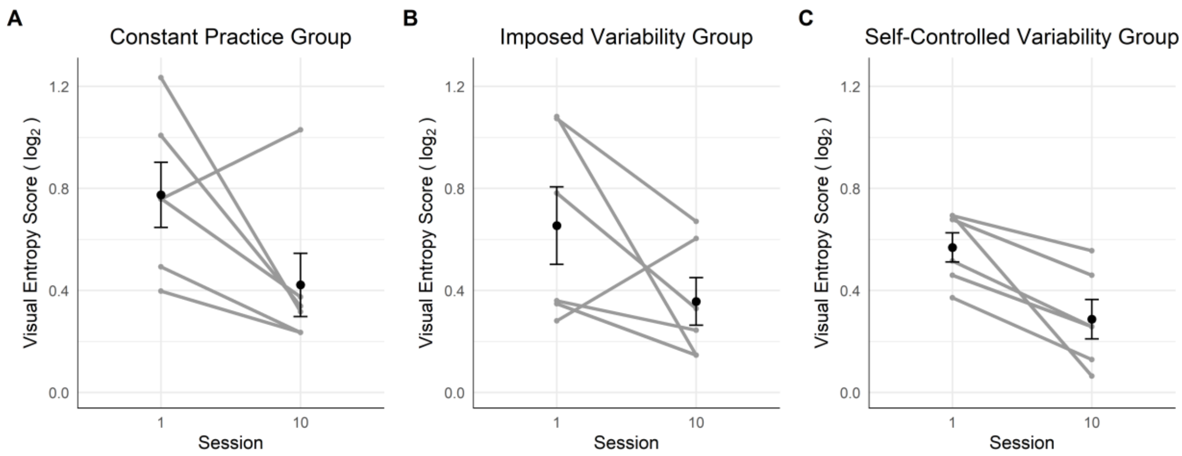

Figure 31. Visual entropy on the transfer route.
Changes in the complexity of the gaze path for the three groups on the transfer route. The black points represent the sessions mean and the error bars their standard error. The grey points and lines represent each participant's dynamics.

Characteristics of the Last Gaze Visit

Offset Time. Figure 32 displays the offset time of the last gaze visits on handholds before touching them. The results of the mixed ANOVA showed a medium effect of the factor Session [$F(1,17) = 16.88$, $p < .001$, $\eta_p^2 = .20$]. The factor Group [$F(2,17) = 0.73$, $p = .498$, $\eta_p^2 = .06$] and the interaction between Session and Group [$F(2,17) = 0.77$, $p = .479$, $\eta_p^2 = .02$] were not significant. The Bayesian mixed ANOVA suggested anecdotal evidence in favor of the null hypothesis for the factor Group (*BF* = 0.43) and the interaction between Session and Group (*BF* = 0.52). The post-hoc test revealed that the visit offset time occurred earlier in session 10 comparing to session 1 (*M* = -72 ms, *CI* = [-109 ms, -35 ms], $p < .001$).

The proportion of online visits was not significantly different between the three groups on session 1 of the transfer route (.53) [$\chi^2(2, N = 191) = 0.964$, $p = .618$] but was on session 10 [$\chi^2(2, N = 190) = 11.87$, $p = .003$]. More precisely, it appears that the CG maintained the proportion of online gaze visit on session 10 as with session 1 [.57, $\chi^2(1, N = 118) = 0.31$, $p = .577$] (**Figure 32D**). However, the IVG group did significantly less online visits in session 10 (.29) than in session 1 (.48) [$\chi^2(1, N = 121) = 4.98$, $p = .026$] (**Figure 32E**). The SVG maintained the proportion of online gaze visit on session 10 compared to session 1 [.49, $\chi^2(1, N = 142) = 3.44$, $p = .064$] (**Figure 32F**).

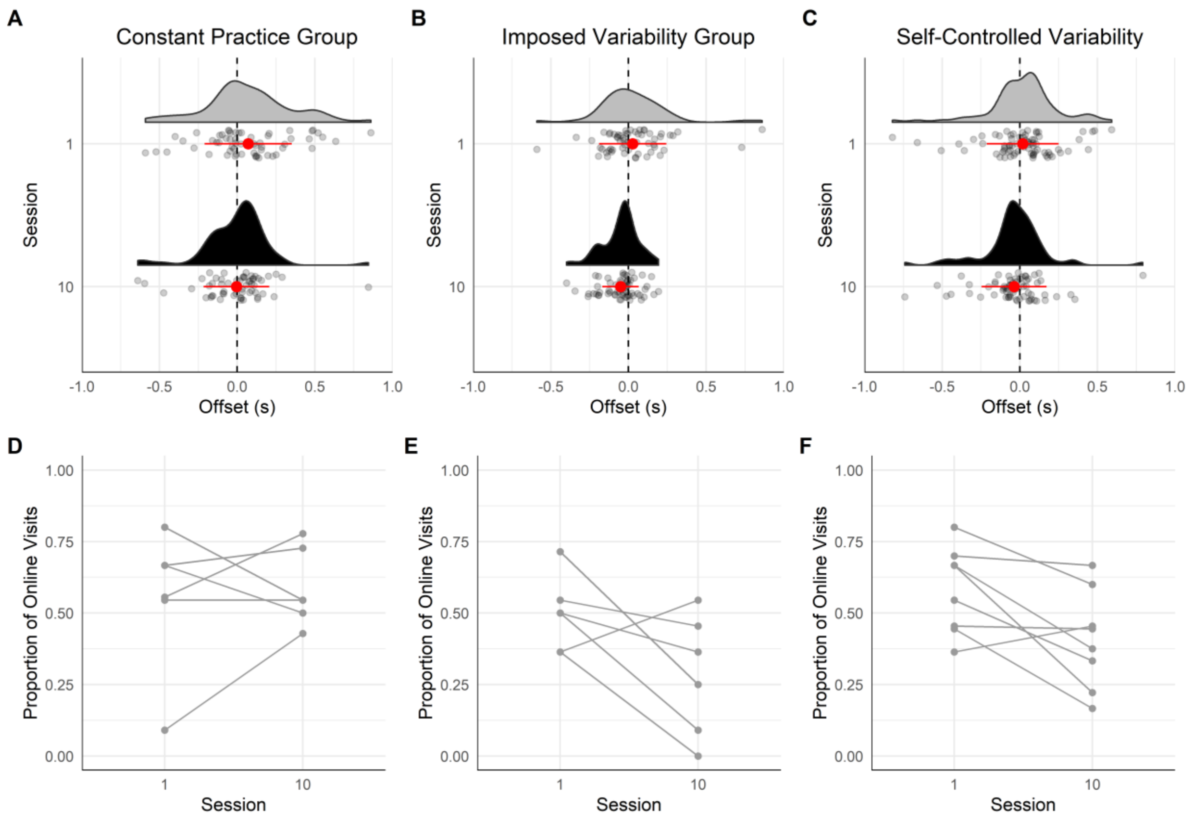

Figure 32. Offset time on the transfer route.
Offset time of the last gaze visit before the hand contacted the handhold for the three groups on the transfer route. In panels A, B and C, the vertical dashed line shows the time the hand touched the handhold, each point represents one gaze visit, the half violin shows the density of points, the red/grey point with the error bar refers to the mean of all the gaze visits and the standard deviation around the mean. The color of the half violin refers to the learning session: in grey, session 1 and in black, session 10. Panels D, E and F displays the individuals' proportion of online visits on session 1 and 10. Panels A and D show data for the constant practice group, panels B and E for the imposed variability group, and panels C and F for the self-controlled variability group.

Gaze Duration. Figure 33 displays the duration of the last gaze visit on handholds before touching them. The Shapiro-Wilk test showed that the assumption of normality was violated for the IVG on session 10. The results of the mixed ANOVA showed a medium effect of the factor Session [$F(1,17) = 10.48$, $p = .005$, $\eta_p^2 = .14$]. The factor Group [$F(2,17) = 1.49$, $p = .253$, $\eta_p^2 = .11$] and the interaction between Session and Group [$F(2,17) = 0.23$, $p = .801$, $\eta_p^2 = .01$] were not significant. The Bayesian mixed ANOVA suggested anecdotal evidence in favor of the null hypothesis for the factor Group (*BF* = 0.57) and the interaction between Session and Group (*BF* = 0.46). The post-hoc test revealed that the duration of the last gaze visit was shorter in session 10 comparing to session 1 (*M* = -100 ms, *CI* = [-165 ms, -35 ms], *p* = .005).

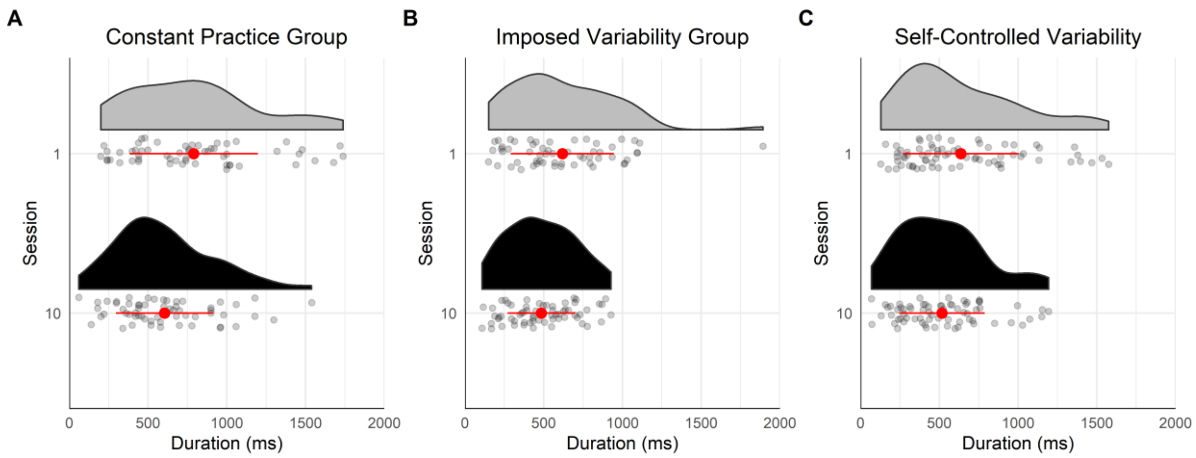

Figure 33. Duration of the last gaze visit on the transfer route.
Duration of the last gaze visit before the hand contact the handhold for the three groups on the transfer route. In panels A, B and C, each point represents one gaze visit before a contact with a handhold, the halves violin shows the density of points, the red/grey point with the error bar refers to the mean of all the gaze visits and the standard deviation around the mean. The color of the half violin refers to the learning session: in grey, session 1 and in black, session 10. Panels A, B and C shows data for the constant practice group, imposed variability group and the self-controlled variability group, respectively.

Discussion

The aims of this paper were to examine how the gaze control of action adapts to different practice conditions and how this may contribute to transfer of learning. For this purpose, we measured the participants climbing fluency and gaze behaviors on a training and transfer route and we compared three practice conditions: a constant practice, an imposed variable practice and a self-controlled variable practice. Results did not show any beneficial effects of variable practice on the learners' climbing fluency on the training route and on the transfer route in comparison to the constant practice group. Moreover, the CG performed better than the IVG on the training route in the last session according to the spatial fluency indicator. The complexity of the gaze path evolved similarly for the three groups on the training and transfer routes with a decrease in variability with practice. Finally, the three groups demonstrated different adaptations of the dual demand of gaze pattern when controlling their hand movements on the training route at the end of the learning protocol: the CG used more online gaze control of their hand movements whereas, in contrast, the IVG used more proactive gaze. The SVG, participants did not change their gaze pattern, that is they maintained a proportion of .41 of online gaze visits. In addition, on the transfer route, only the IVG adapted the gaze control of hand movements in a similar fashion as the training route in the last session.

Climbing Fluency

Specificity of the Individual-Environment Coupling

The Bayesian analysis indicated evidence in favor of the hypothesis that the three groups showed similar improvements of climbing fluency on the transfer route. Previous research in perceptual-motor learning has revealed benefits from variable practice for the transfer of learning (Fajen & Devaney, 2006; Huet et al., 2011). The benefits were attributed to the attunement of the participants to more reliable information with practice, as the less reliable information (usually initially used by novices) became less useful when varied across trials. Therefore, in the present study, we expected that by varying the layout of handholds on the wall during practice, the participants in IVG would attune to higher-order information to specify the possible climbing movements in the different routes. However, the results showed similar benefits from constant and variable practice in the transfer route. The findings in the current study may be explained by the complex learning environment that may foster sufficient exploration, even during CG practice. Indeed, the CG practiced on a climbing route that offers a range of opportunities for action, which, in contrast with the virtual learning environment used in the previous studies (Fajen & Devaney, 2006; Huet et al., 2011), invites more perceptual-motor exploration during practice. Thus, CG may have benefitted from their intrinsic variability to discover a large range of information-movement couplings, which facilitated performance on the transfer route.

The benefits of the exploration within a constant learning environment is also supported by the lower complexity of the hip trajectory on the last session of the CG than the IVG on the training route. Indeed, this measure was designed to assess the degree of coherence in information-movement couplings (Cordier, Mendés France, et al., 1994) and was recently reported to be associated with climbing efficiency (i.e., a lower complexity is linked to lower energy expenditure) (Watts, España-Romero, Ostrowski, & Jensen, 2019). Thus, the difference between the two groups suggests that the CG have benefited from practice on the CG training route to discover improved information-movement couplings. This appears in line with Gibson and Gibson (1955) proposition that individuals learn by differentiating information about environmental properties. Moreover, the participants in the IVG and SVG did not appear to benefit from their practice on the variations of the climbing route to improve their climbing fluency on the training route to the same extent as the CG. Thus, the results suggest that for novice climbers, the relationship between performance improvements and the practice environment is highly specific, meaning that practice on the variable routes did not adequately transfer to the original training route. However, it remains to be seen whether more skilled participants would benefit from practice in variable environments to better improve in their performance on the original climbing route.

No Benefit of Self-Controlled Practice on Climbing Fluency

Overall, SVG had a lower variability of practice conditions than IVG during their practice as they could only slow the rate of change in practice conditions but not increase it (**Table 22**). We expected that SVG would be more respectful of individual learning dynamics, thus, resulting in better learning outcomes than the imposed exploration intervention (IVG and CG). However, no differences in climbing fluency were observed between the three groups at the end of the practice period on the training route and on the transfer route. However, it is interesting to observe that participants chose to keep the same variants on the route in the final sessions as well as the first sessions (Table 23). This observation differs from the practice schedules observed by Wu and Magill (2011). In their study, participants controlled their practice between three variations of a key-pressing task, and most participants chose to start with a blocked pattern of practice before finishing with rapid switches between the variations. In the current study, the chosen practice schedules of the SVG suggest that participants were initially more attracted by novelty before practicing a smaller range of climbing routes in the final sessions. This practice structure, from initial variability, reducing to blocked conditions may not be an optimal path for safely exploring and discovering the possible task solutions across the different routes. Therefore, it would be necessary for further research to investigate the effect of early variations on the effectivity of exploration in comparison to variations occurring later in the practice period (Hacques, Komar, Dicks, & Seifert, 2020).

The absence of differences in climbing fluency between IVG and SVG contrasts previous research on autonomy-supportive interventions (e.g., Lemos, Wulf, Lewthwaite, & Chiviacowsky, 2017; Lewthwaite, Chiviacowsky, Drews, & Wulf, 2015) that showed (i) an increase in performance, even when the choice affects an irrelevant feature of the task (e.g., the color of a golf ball in golf putting, Lewthwaite et al., 2015) and (ii) improved performance on a transfer task when participants were given control over their practice schedules (Wu & Magill, 2011). One possibility is that the result of the present study may be due to the duration of the practice period (5 weeks), which is longer and may therefore offer greater insight into the learning process than previous self-controlled research. A review of self-controlled practice interventions (Sanli et al., 2013), revealed that practice took place over four days at maximum and most of the reviewed studies had practice completed in one day. Thus, the five weeks practice schedule in the current study may have diluted the perception of autonomy and associated motivational effect on performances. Moreover, in previous research. the autonomy offered to participants tended to be right after each trial (e.g., they chose to receive feedback or they chose the task condition for the following trial), whereas in the current study, the choice made by the SVG was with reference to the following learning session. Thus, the design of our study may have decreased the participants' perception of control over their learning environment as the delay between the choice and its effect is much larger than in previous studies (Sanli et al., 2013). This may have prevented the motivational effect of the intervention in the SVG as according to the Control Effect Motivation hypothesis, motivation is sensitive to one' s control over the upcoming events (Eitam, Kennedy, & Higgins, 2013; Wulf & Lewthwaite, 2016). This potential temporal effect of autonomy on motivation and performance needs to be further investigated.

Gaze Behaviors

Online Gaze Control Enables Better Climbing Fluency?

The CG relied more on online gaze control of their hand movements than the IVG, who conversely, showed more proactive gaze control with practice on the training route. This contrast explains the better climbing fluency for CG on the training route. Previous studies demonstrated that online gaze control supports more accurate stepping behavior (Chapman & Hollands, 2006b) and that when walking over rough terrain, participants look a shorter distance ahead than when the terrain is flat (Matthis et al., 2018). Thus, comparable to these examples, participants in CG tuned their gaze behavior to perform their climbing movements as accurately as possible by exploiting proximal locations of the training route. The increase in the use of online gaze control with practice, enabled CG participants to further improve the chaining of their actions and their climbing fluency scores due to their extensive practice on the training route.

Conversely, IVG used more proactive gaze control following practice on the training route. This result showed that IVG participants tuned their gaze behavior to anticipate the constraints on future movements. This kind of gaze pattern has also been observed in natural tasks, when participants perform a series of action during goal achievement (Johansson, Westling, Bäckström, & Randall Flanagan, 2001; Land et al., 1999). That is, participants look at an object that they were about to manipulate (e.g., a cup) before reaching it (Land, 2009). With such gaze behavior, Land (2009) proposed that performers free their visual system as soon as other perceptual systems (e.g., haptic) are in sufficient contact to regulate the movement. Similarly, studies on the development of locomotion showed that infants relied more on online control than children and adults when walking in a room with obstacles (Franchak & Adolph, 2010; Franchak et al., 2011). Thus, it appears that the participants in the IVG showed changes in gaze behaviors similar to those observed in the development of locomotion with a gaze behavior that, with practice, is used to guide the hand movements rather than to control them, so that participants use more haptic information with practice (Huys & Beek, 2002). These gaze behaviors may support fluent climbing; however, it appears that to reach higher climbing fluency, visual information during the contact phase is necessary.

In the development of locomotion, research has indicated that the gaze behavior of infants was different in quadrupedal locomotion (crawling) than when walking (Franchak et al., 2011). Moreover, gaze control during quadrupedal locomotion used more online gaze control than walking, in a similar fashion as reaching for object (Franchak et al., 2011). Thus, as our study focused on the gaze control of hand movements, our results may not be directly applicable to the control of foot movements while climbing, as the literature suggests that more proactive (or even peripheral) control of action is preferred for foot placements when the task demand allows lesser accuracy demands of foot placement (Chapman & Hollands, 2006b; Franchak & Adolph, 2010). Future studies may investigate further gaze control of action in climbing to better highlight the differences of how hand and foot movements are controlled with the visual and/or the proprioceptive system (e.g., Mantel, Stoffregen, Campbell, & Bardy, 2015).

Proactive Gaze Control Cooperates with the Transfer Route

In line with our hypothesis that the CG would develop a gaze pattern highly specific to the training route while IVG would lead to a more adaptive gaze pattern, results showed that the more proactive gaze strategy of the IVG on the training route was also observed on the transfer route. In contrast, the CG showed a similar fixation offset time on session 1 and 10 of the transfer route. Thus, although the climbing fluency measure did not indicate that variable practice facilitated transfer, the gaze behavior developed during practice led to the development of an exploratory (proactive) gaze behavior that was adapted to the task demand of a new climbing route (Seifert, Wattebled, et al., 2016; Zanone & Kelso, 1997). Conversely, the gaze behavior developed by CG on the training route was not utilized on the transfer route as participants reverted to the gaze behavior used on session 1 of the transfer route. Thus, for CG, the gaze behavior developed with practice competed with the task demand of the new route, compromising general transfer (Seifert, Wattebled, et al., 2016; Zanone & Kelso, 1997). Considered in tandem with the climbing fluency results, repetition of practice conditions is necessary to improve performance but extensive practice within the same conditions appears to "overspecialize" gaze behaviors, which limits adaptability. Overspecialization in this context refers to the learner becoming attuned to information that is variant across other environmental conditions (Smeeton et al., 2013). In contrast, participants in the IVG "learned to explore", that is, they developed a gaze pattern that facilitated the pick-up of information to act adaptively under new constraints (Hacques et al., 2020). Thus, the present study illustrates that learning and becoming skilled is not only revealed by the performatory activity (i.e., the coordination pattern used and the associated performance) but also by the changes in exploratory behaviors underpinning performatory activity (Hacques et al., 2020).

Self-Controlled Group Stayed in a Comfort Zone during Practice? Or Did they Show Different Individual Benefits?

Although practicing on the variable routes, the participants in SVG did not significantly change the time of fixation offset. Therefore, in comparison with IVG participants who adapted their gaze behavior, SVG did not adjust gaze patterns, which may be a function of the comparative decrease in the amount of variability during practice for SVG. This result suggests that participants in SVG chose (i.e., whether to train on a new variant or not) to remain within a comfort zone during practice (Liu et al., 2012). Nevertheless, when individual data is considered, the effects of practice on the training route are distinct between SVG participants (**Figure 28**). Five of the eight participants clearly showed less online gaze control of their climbing movements on the transfer route (**Figure 32**). Thus, rather than all participants remaining in a comfort zone, it appears that on the training route, some developed a gaze behavior similar to CG while others were similar to IVG. These interindividual differences highlight the importance of considering variability in gaze patterns (Dicks, Button, et al., 2017), revealing that some participants may have developed both gaze patterns and used them adaptively according to the task demands. Although, we did not manipulate the route difficulty, the confrontation to a new route is in itself more difficult than climbing a known route. Self-controlled practice may therefore represents a means to enable individualization of how challenging the learning environment is during practice (Keetch & Lee, 2007; Y.-T. Liu et al., 2012). Further investigation on the individual learning pathways may be productive in better understanding how learners can benefit most from such interventions.

Summary and Future Directions

This study followed previous work that acknowledged the importance of the timing of the information pick-up in complex perceptual-motor tasks (Navia et al., 2017). The findings of the present study highlighted that information pick-up was affected by practice conditions. This may explain why variable practice facilitates transfer of learning while constant practice may lead to an overspecialization of individuals to the learning task constraints. Extant literature indicates that behavior and performances in complex perceptual-motor tasks follows a nonlinear learning process (Chow et al., 2008; Nourrit et al., 2003; Orth, Davids, Chow, et al., 2018). In contrast, the learning dynamics of changes in gaze patterns during learning remains relatively unexplored (Hacques et al., 2020). Thus, the results from the current study, particularly given the interindividual variability in SVG suggests that a challenge for future investigations is to reveal the individual learning dynamics of information pick-up in tandem with behavioral dynamics. We may expect to observe different gaze patterns to achieve similar task outcomes within and between individuals, highlighting degeneracy in perceptual-motor control (Dicks, Button, et al., 2017). Such investigation may further understanding of why some individuals develop better adaptability than others, even when exposed to the same intervention.

General Discussion

Introduction

This work aimed to further the understanding of skill learning and transfer in complex-perceptual-motor task. More specifically, this work investigated (i) the changes in exploratory activity that accompany learning and support transfer in a climbing task and (ii) the effects of infusing imposed and self-controlled variability in practice. The purpose of this concluding section is to summarize the main findings of the studies reported in the preceding section while presenting the theoretical and applied implications. First, the main findings of the chapters 4 to 7 are reviewed. Second, the theoretical contributions of this thesis are presented, with respect to its limitations. This part also presents some perspectives. Finally, the practical applications of this thesis in skill learning in sport and physical education are proposed.

Summary of the Main Findings

In a first experiment presented in the chapter 4, the aims were (i) to investigate the modifications of learners' visual and haptic exploratory activity with practice and (ii) to examine to what extent route finding skills could transfer from one climbing route to another with new handholds properties. First, we hypothesized that with learning exploration would be increasingly used to guide actions rather than searching for affordances. Second, we hypothesized that learners' skill transfer to a new performance context would depend on the magnitude of the disturbance in the information-movement induced by the new environmental properties. To test the latter hypothesis, three transfer routes were designed by modifying the handhold properties (i.e., increasing the distance between handholds, turning the handholds or changing their shape) of the route on which participants trained during 10 sessions. The results showed that the number of exploratory actions (fixations and exploratory hand movements) decreased, and that gaze behavior gained in goal-directedness, suggesting that the function of exploration changed with learning, from discovering the properties of the environment to guiding the climbing movements. Results also showed that the new handhold properties of the transfer routes had different effects on the participants climbing fluency and exploratory activity. It appeared that skill transfer was more effective when the new properties encouraged low-order behavioral changes in the climbing movements (i.e., more amplitude in the climbing movements due to increased distance between handholds), than when they invited high-order behavioral changes (i.e., different body postures in relation to the different handholds orientation). It also appeared that changing the shape of the handholds prevented skill transfer because the complexity of the handholds shape did not explicitly offer a way of coupling this information to movement, but instead requested more exploration to be exploited. This was notably highlighted by the absence of relationship between the change in the organization of the gaze path and the change in climbing fluency which suggested that participants continued searching for affordances in this route post practice.

Chapters 5, **6** and **7** referred to a second experiment where the objectives were (i) to examine whether infusing variability in practice would foster skill learning and transfer and (ii) to investigate whether variable practice conditions could be optimized by giving learners the opportunity to self-control the frequency of variations in the task and by extension the amount of total variability encountered during practice. We expected that variable practice conditions would increase learners' exploration during practice in comparison to a constant practice condition, which would (i) improve learners' behavioral flexibility, (ii) enhance their learning rate and (iii) guide the development of visual exploratory activity facilitating adaptation to new performance contexts. We also expected that these outcomes would be optimized with self-controlled variable practice as it would offer practice conditions that are more respectful of the individual learning dynamics by enabling learners to better exploit their relationship with the different learning contexts. Thus, our study design involved three practice conditions: a constant practice condition, an imposed variability condition and a self-controlled variability condition.

In this experiment, the climbing task was different from the task used in the **Chapter 4**. This was motivated by the insurance that participants on this new route aimed to focus on movements chaining through the climbing route rather than grasping the single handholds. Thus, we controlled the shape (hence the complexity) of the climbing holds by using a single model of holds for handhold and foothold to design all the routes (**Appendix A, Figure 36**). Moreover, we added the prompts to use all the handholds and to use them in the bottom-up order.

Learning is characterized by a reorganization of the performers' behavioral repertoire (i.e., intrinsic dynamics). In the designed climbing task, performers were required to use two different hands coordination patterns in different handholds configurations. Therefore, the **chapter 5** examined (i) whether the variability infused with practice on task variations would improve the flexibility of these hand coordination patterns and (ii) whether the self-controlled practice would lead to lower interindividual differences by enabling learners to exploit these patterns more optimally. The participants' flexibility was tested by manipulating two forms of task constraints: the route design and the verbal instructions. These manipulations could be either neutral, congruent, or incongruent according to the coordination patterns they invited to perform. The results showed that participants learned a new coordination pattern (i.e., the hand repetition pattern) and improved their flexibility as they could use the two coordination patterns in different route designs – instruction conditions. Contrarily to our expectations, the constant practice condition appeared to support the development of behavioral flexibility as much as the imposed variability condition. However, the self-controlled variability condition appeared to have facilitated the participants' development of their behavioral flexibility. Indeed, all the participants from this group remarkably showed adequate hand coordination patterns in all the different sets of constraints, particularly in the incongruent conditions where, in contrast to the other groups, they all showed similar and adapted coordination patterns on the posttest.

In the chapter 6, the aims were to examine the effects of the practice on new climbing routes on performance and behavioral variability and to examine whether the self-controlled practice condition would be more beneficial to performance than the imposed condition. We expected that the confrontation to various performance context would increase behavioral variability, which would improve the learning rate and performance on a transfer test. We also expected greater improvement of performances in self-controlled conditions than in imposed conditions of practice. The results showed as expected a higher behavioral variability during practice when performers were confronted to various performance contexts than in constant practice conditions. However, the results did not support that this increased variability benefited participants' learning rate and transfer. The results rather suggested that skill learning was specific to the performance context, although some general transfer could be observed between the different performance contexts. Results also reported that learners in the self-controlled group showed less inter-individual variability in their performance curves than the learners in the other practice conditions, which suggests that the opportunity to control the task may have helped learners individualize the exploitation of the variable practice conditions. We proposed that the self-controlled condition may encourage learners to more actively self-regulate their performances, as it favors learners' engagement in the design of their practice conditions and it gives them freedom to explore different movements (Otte et al., 2020; Woods, Rudd, et al., 2020).

The literature investigating the visual control of locomotion showed that the gaze behavior in locomotor tasks is constrained by a dual demand: controlling the current action and anticipating the future constraints on movements. In the chapter 7, the aim was to investigate the effect of the three practice conditions on how learners deal with this dual demand on their gaze behavior. We expected that the variable practice conditions would foster proactive gaze behaviors, which would facilitate the adaptation to climbing a new route. Conversely, we expected that the extended practice in the same learning environment (i.e., constant practice condition) would promote online gaze control of climbing movements, which would not be adapted when climbing a new route. Thus, in addition to the analysis of the gaze path, we examined the gaze behavior in relation to the hand movements. More precisely, we were interested in the latest period of time where the gaze was directed toward the handhold about to be grasped (i.e., the last gaze visit of the handhold starting before that the hand touched the handhold). The results showed that this last gaze visit was affected by practice, as its duration shortened, and the offset time shifted. However, the direction of the shift differed between the three practice conditions. The constant practice conditions appeared to foster online gaze control of actions by shifting the gaze visit offset after that the hand touches the handhold whereas, the imposed variability condition had the opposite effect, that is engaging learners with a more proactive gaze behavior, as the offset time occurred before the hand contact with the handhold. Finally, the self-controlled variability condition did not show any significant effect regarding the offset time as learners in this condition showed various trends. On the transfer route, only the learners from the imposed variability group demonstrated a similar change in offset time as on the training route, suggesting that their proactive gaze behavior developed with practice could be transferred to a new performance context.

Implications for Theory

Exploratory Activity Becomes More Action-Relevant with Practice

According to the Ecological Dynamics theoretical framework, skill learning consists of improving the functional fit between an individual and a particular performance context (Araújo & Davids, 2011). The mutual and reciprocal relation between the performer and his/her environment is captured through the information-movement couplings: performers actions generate perceptual information that is used to guide actions. Previous studies showed that performers can learn to rely on more reliable information for action with practice (e.g., Fajen & Devaney, 2006; Huet et al., 2011). In the current thesis, the main objective was to focus on the information-movement couplings by examining the changes in performers' exploratory activity that accompany skill learning and support skill transfer in a climbing task.

The **Chapters 4 and 7** focused on the visual exploratory activity of the learners. In these two studies, we aimed to characterize the gaze search behavior of the participants during the climbs and, more specifically, the displacement of the gaze in the performance environment (i.e., the climbing route). In this purpose, the usual commonly reported fixations variables (i.e., the number and duration of fixations in relation to their location) appeared as insufficient. Thus, a measure of visual entropy was used to assess the level of organization of the participants' gaze path. The results indicated a gain in organization of the visual search behavior characterized by a more direct gaze path. In **Chapter 7,** the results even showed that during last session some participants were not searching at all: their gaze went from handhold to handhold in the same order as handholds were used to climb the route. These changes in the gaze path and the positive correlation of the visual entropy with the climbing fluency observed in **Chapter 4** suggest that participants initially used their gaze activity to discover their surroundings, and, with practice, they learned to use their gaze activity to guide their climbing movements. This suggests that the dominant function of the eye movements during performance changes with learning meaning that exploring for affordances decreased whereas exploiting information-movement couplings became the main function with practice. Such change in the function of the visual exploratory activity was also proposed to occur during the performance of a single goal-directed action. Van Andel, McGuckian, Chalkley, Cole, & Pepping (2019) proposed that, when performers are surrounded by affordances, the visual exploratory activity has the functions to discover the opportunities for action and specify the movement requirements. These functions were respectively labelled as "exploration for orientation" and "exploration for action specification" and were hypothesized to show differences in terms of movement patterns (van Andel et al., 2019). As exposed previously, the dominant function of the gaze behaviors appears to change with learning and this differentiation of exploration for orientation and exploration for action specification may fit this change. However, it should be stressed that even in early practice, learners need to guide their movements and they may still discover new affordances with practice. Therefore, there may be a dominancy of one function over the other, but the two functions would still contribute to each other and, more generally, to the improvement of the functional fit between the performer and his/her performance context. We may expect that the dominancy of one function over the other would show a nonlinear dynamic during practice, as learners would alternate between exploring new opportunities for action and exploiting information-movement couplings.

As already observed in previous studies, the analysis of learners' gaze behaviors in laboratory tasks suggested that gaze behaviors become more task-relevant with learning, as participants made fewer fixations and changed the location of fixations with learning (de Brouwer, Anouk, Flanagan, & Spering, 2020). Given our results and those of previous studies investigating gaze behavior in naturalistic tasks (e.g., Land et al., 1999), even novice performers appear to direct their gaze toward task-relevant areas, including when performing in cluttered environments. For example, in the first experiment although various holds irrelevant for the climbing task were on the climbing wall, the participants directed their gaze toward the holds corresponding to their climbing route and the relative duration of fixation time spent fixating relevant holds was not affected by practice. What changed, however, was the organization of the gaze path and the number of fixations toward the climbing holds. Thus, presenting the task goal to the participants appears to have been sufficient for participants to narrow their attention to the task relevant areas of the route during the climbs, although the time given to preview may surely have helped to locate the relevant holds. These observations are in line with the Ecological Dynamics view that performers' intentions direct their attention to functionally explore their environment for actions and achieve their task goal (Button et al., 2021). Therefore, rather than guiding gaze toward task-relevant areas of the route, we propose that learners' intentions constrained the gaze actions toward relevant areas in the environment, and practice improved information-movement couplings which organized the gaze behaviors to guide movements performance, making gaze behaviors more action-relevant with learning. This was clearly shown in the **Chapter 7** by the participants in the constant practice group who were only looking toward handholds that they were about to use. Similarly, the two other groups were at most looking toward the handhold that directly followed the on-going targeted handhold.

Therefore, gaze behaviors appear to become more relevant to limbs' actions with practice in the climbing tasks.

As presented in the **Chapter 2**, when considering the dynamical coupling between information and movement, the effective control of movements does not primarily depend on the duration and location of fixations as suggested by the quiet eye literature, but depends on the timing of the gaze movements in relation to body movements (Oudejans et al., 2005). In the **Chapter 7**, we emphasized that climbers needed visual information to both control their ongoing movements and anticipate the upcoming constraints. For the participants, the designed climbing tasks emphasized the importance of appropriately addressing this dual demand, notably by demanding to participants to chain their climbing movements fluently. Thus, the gaze behaviors were linked to the hands' actions to examine how participants dealt with the dual demand with practice. The results showed that the constant practice condition promoted the control of ongoing movements while the imposed variability condition promoted the anticipation of future constraints. These results highlight that the history of the interactions between performers and learning contexts shapes how performers balance their gaze behavior to address to the dual demand on their visual system.

Although we could present within-participants changes in gaze behaviors between early and late practice, a future perspective would be to explore the dynamics of change in gaze behaviors to inform how learners modify their use of their visual system as they improve their functional fit with their performance context. To our knowledge, the dynamics of the gaze behavior was only presented in Sailer, Flanagan,& Johansson (2005), but the three proposed learning stages (exploratory phase, skill acquisition and skill refinement, see **Chapter 2** for more details) appear to apply specifically to their interception task. As an exploratory study, we looked at changes in the gaze variables used in **Chapter 7** at two timescales: within the first and the last session and between early and late practice (**Appendix B**). The results showed that the gaze path was more organized only within the six trials of the first session, but the characteristics of the last gaze visit only changed between the session 1 and 10 (there was no within-session effect). These exploratory analyses suggest that exploration for affordances decreased more rapidly than the information-movement couplings were optimized, supporting that different aspects of gaze behaviors would show different dynamics. Thus, as for coordination patterns, we may expect learners to demonstrate different (nonlinear) dynamics according (i) their attunement to their environment and (ii) to their intrinsic dynamics.

Educating Attention with Practice Conditions

As presented in the **Chapter 3** reviewing studies setting up variable practice conditions, a major part of this literature is based on information-processing theories which propose that benefits of variability in practice to transfer would be due to the development of representational structures (e.g., the Schema Theory) or improved internal processes (e.g., Contextual Interference, Structural Learning). The current thesis supports and complements the Ecological Dynamics approach to variable practice and transfer, considering that the benefits of variable practice conditions are due to exploratory activity facilitating information-movement coupling. Previous studies showed that the learners' attunement could be guided by manipulating the practice conditions, and notably by reducing the reliability of some informational variables with variable practice conditions (Fajen & Devaney, 2006; Huet et al., 2011). In these studies, the education of attention consisted of relying on a new informational variable. Oudejans, Koedijker, Bleijendaal, & Bakker (2005) proposed that educating attention also consisted of learning to pick up information at the appropriate time if we consider the dynamic nature of the information-movement coupling. Thus, in the **Chapter 7**, we investigated whether variable practice conditions would affect this form of education of attention and examine whether it would benefit skill transfer. Our results provided evidence supporting this hypothesis, as the constant and imposed variability conditions induced different changes in visual control of movements with practice and only the imposed variability group showed similar changes in the transfer task. However, both interventions showed similar changes in climbing fluency on the transfer route, which limits the confirmation of our hypothesis. The issue may reside in the design of the protocol and notably in how we assessed transfer. As we were interested in skill transfer, that is the ability to transfer a skill from the learning context to new context, the transfer test was performed post practice with a single trial on a new route. The focus on skill transfer was motivated by maintaining ecological validity with respect to performance contexts in climbing generally demanding to performer to be successful in a single trial (this is even named by climbers as climbing on-sight). However, the benefit of the change in exploratory activity induced by the imposed variability condition may rather be observed with more trials in the transfer context. Indeed, we may expect that the change in exploratory activity would improve the learning rate in a new context. This would refer to transfer of learning, or the “learning to learn” phenomena. Such benefit of the exploratory activity was notably emphasized in the development of locomotion (Adolph, 2008). According to Adolph (2008, pp. 3–4) learning to learn in this domain is characterized by (i) adaptive responses to novel problems within the boundaries of a given problem space, (ii) a flexible variety of solutions compiled on the fly rather than a fixed solution drawn from an existing repertoire and (iii) the failure to transfer outside the boundaries of a problem space (e.g., failure to transfer of learning from crawling to walking, Adolph, Bertenthal, Boker, Goldfield, & Gibson, 1997). These characteristics emphasize that learning to learn implies exploratory activity that supports the successful achievement of the task goal. However, in contrast to the tasks used in the study of the development of locomotion, our climbing task requires that, in addition to successfully reach the top of the route, the climbers do it while chaining their movements as fluently as possible. This requirement for performance entails that, although all performers were able to climb the transfer routes, they also need to explore the different possibilities of chaining their movements to optimize performance. Therefore, on the basis of Adolph’s characteristics of learning to learn (2008), we may expect that the dynamics of adaptation to the new context would differ according to the practice condition. In particular, we may expect that the proactive gaze behaviors and likely larger pannel of experienced information-movement couplings developed during the variable practice conditions would improve the search of an adapted movements chaining in comparison to the constant practice condition.

Variability in Constant Practice Conditions

Studies showed that skilled climbers perceive the climbing routes functionally: they perceive what climbing movements the holds configurations afford (Boschker et al., 2002; Pezzulo, Barca, Lamberti, & Borghi, 2010). The variable practice conditions were designed in the aim of improving participants’ perception of affordances on climbing routes (which would facilitate skill transfer) and to develop their behavioral flexibility by confronting them to various holds configurations. Contrarily to our expectations, the participants in the constant practice condition showed similar improvement (i) in climbing fluency on the transfer test and (i) in their behavioral flexibility. These results highlight some limitations in the generalization of findings from simple perceptual-motor task to more complex ones. The rich landscapes of affordances that complex multi-articular tasks offer to the learners provide them with the opportunity to explore different movement solutions. Indeed, the training route requires climbers to perform multiple movements in a single trial. In the first experiment, this variability in movement patterns was even more important as the route was longer and the handholds afforded various grasping patterns. This possibility for variability may explain the improvement in behavioral flexibility that we observed in the constant practice condition and it may also explain the similar improvements in climbing fluency on the transfer route. Thus, we may expect that these benefits of constant practice would not be observed (or in a much lesser extent) if the design of the training route were simplified to limit the opportunities for action (e.g., a route design similar to the routes used during the scanning procedures).

The constant practice condition also enabled learners to demonstrate better climbing fluency on the training route. This suggests that the extensive practice enabled the learners to more finely tune their information-movement couplings to the properties of this performance environment. Also, the higher behavioral variability observed in the other practice conditions did not benefit performance on the training route (**Chapter 6**), suggesting that the benefits of exploration were specific to the performance context. However, this difference in behavioral variability may also be due to increased exploitation in the constant practice condition that would have fostered fine adjustments in the chaining of the climbing movements. To address this question, a solution may be to investigate more finely the behavioral variability of the participants by looking into the dynamics of their chain of actions. In the **Chapter 6**, the behavioral variability was assessed based on the hip trajectories of the participants, which was used to reflect the displacement of the center of mass of the participants (although the method used only provides an approximation of this center of mass), thus, providing a view of the performed movements at a macro scale of analysis. The variations observed in hip trajectories can be due to changes in postural regulation as well as changes in hand and feet movements and invite to conduct a micro-scale analysis. Therefore, our next aim is now to investigate the dynamics of movements chaining performed by climbers when practicing on the training route. That way, we would be able to locate the changes in limbs movements and examine how climbers organized their exploration of the route. However, to achieve this, a deeper analysis of the kinematics of the climbers is necessary. In fact, we already accessed the contact times of the hands and feet on each hold (**Figure 34**), which will be soon complemented by the limb movements obtained with pose estimation performed on the video recordings of the trials (**Figure 35**). This will provide a precise measure of which specific limb is in contact with which specific hold. Hopefully this new project will reveal the effects of the practice conditions on the dynamics of the change in movements chaining.

A **B**

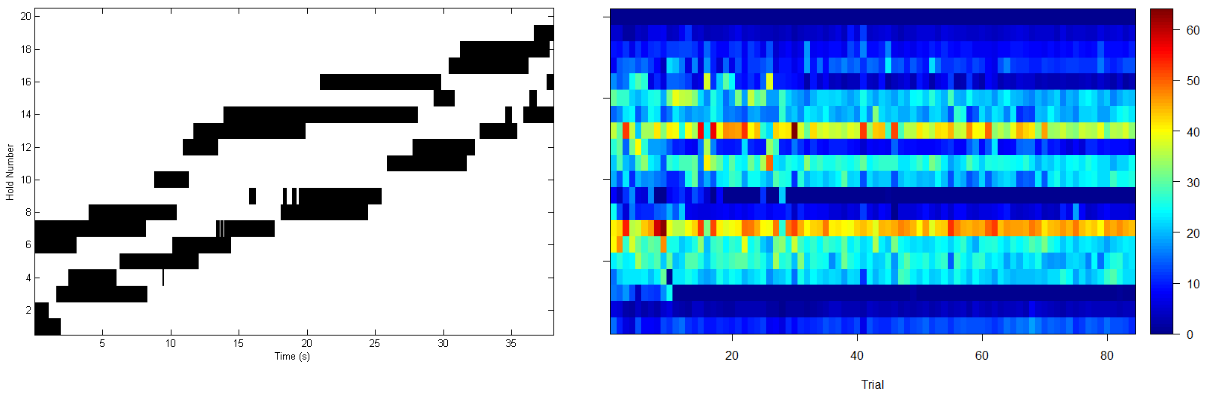

Figure 34. Performance and learning dynamics obtained with the instrumented holds.
Panel A shows the duration of the limbs contact with the holds on the training route during a single trial. Panel B shows for each of the 84 trials performed on the training route the relative duration of contact with the hold (in percentage of the total climbing time). In both panels, each line corresponds to a climbing hold of the training route.

Figure 35. Pose estimation of the climbing behavior.
The picture is a frame from the video recording of a climb on the training route. The colored lines represent the estimation of joints and segments locations obtained with pose estimation.

Enhancing Active Self-Regulation with Self-Controlled Practice?

The current thesis hypothesized that giving learners the opportunity to control the rate of variations during practice would optimize learning in comparison to an imposed rate of variations. The results did not fully support this hypothesis as none of the group comparisons performed in **Chapters 5 and 6** showed statistically significant differences between the two groups with variability. However, we could highlight some interesting trends regarding the individual results. First, the **Chapter 5** showed that all the participants in the self-controlled practice condition were able on post-test to adapt to the different set of constraints designed for the test sessions. Notably, the self-controlled group was the only one for which participants showed expected hand coordination patterns in the divergent instruction-route design conditions. This suggested that they were able to exploit the degeneracy (i.e., the ability to perform similar function with different body structures; Seifert, Komar, Araújo, & Davids, 2016) of their perceptual-motor system to adapt to the different set of constraints of the tests sessions. The demonstration of such adaptive behaviors characterizes the exploitation stage of the three-stage model of learning proposed by the Ecological Dynamics framework (see the presentation in the **General Introduction**, Button et al., 2021, p. 131). Second, the performance curves of the participants in this condition interestingly showed lower interindividual variability comparing to the other groups (although, one participant showed a different performance curve than others, **Chapter 6**). Taken together, these results suggest that the self-controlled practice condition was effectively more respectful of individual learning dynamics. This contrast between the different practice schedules and the similar learning outcomes demonstrated by participants emphasizes that a learner-centered approach may be more suitable than "one-size-fits-all" intervention when training supra-coordinative skills (Chow et al., 2016). The self-controlled condition may have encouraged participants to actively self-regulate during performance, that is "to interact with the environment by solving problems, seeking and detecting information, utilizing affordances and (re)organizing goal-directed actions based upon one's intentionality and the constraints of the environment" (Woods, Rudd, et al., 2020, p. 4). Enhancing active self-regulation would contribute to help learners navigate autonomously through their constantly evolving performance landscape. This wayfinding activity is considered as learning to adapt to unfamiliar performance contexts by connecting to the environment (Woods, Robertson, Rudd, Araújo, & Davids, 2020). This Ecological Dynamics view of self-regulation and wayfinding entail that learners are engaged in the design of their practice conditions, and that they are given freedom to explore different movement solutions (Otte et al., 2020). Thus, the lower inter-individual variability observed in the learning outcomes of the self-controlled group may have been due to an enhanced engagement of learners with their learning environment during practice, notably in comparison to the imposed variability group, which appears to be a more challenging learning condition, and maybe too challenging for some of the participants. Yet these speculations need to be properly investigated. The examination at an individual level of the motivations behind the choices to keep or change the routes may further understanding of how learners engage with their learning conditions. Looking into their performance and behavioral dynamics in relation to their choice may be a first perspective to explore.

From Research to Practice: Practical Implications

Training Exploration

Before presenting some potential applications for skill learning in sport and exercises, we would like to highlight a direction that should not be avoided based on our findings. Previous research on gaze behaviors or visual exploratory activity comparing novices to experts could often propose to train the lesser skilled performers so that they copy or simulate the experts' behaviors with a prescriptive perceptual training (e.g., Jordet, 2005; Klostermann, Vater, Kredel, & Hossner, 2015). Although such intervention may enhance performance in a particular situation, it would not improve the performers adaptive skills, which is considered as a central goal in the ecological dynamics framework (Araújo & Davids, 2011). In the current thesis, the gaze behaviors of the participants changed as they were finding ways to adapt to the constraints applied to their activity. Thus, exploratory activity emerged from a self-organization process. The constraints manipulated during training should be designed to guide the performers to find adapted (now) and adaptive (for the future) solutions. Moreover, as the exploratory activity only enables a facilitated access to information, performing a similar exploratory activity from one individual to another without proper attunement to the information is useless. For example, novices and experts may look at the same climbing wall but perceive different affordances (or even no affordances) due to their difference in attunement (Pezzulo, Barca, Bocconi, et al., 2010). It stresses the importance for coaches and practitioners to have in mind that the visual system is constrained by a dual demand. Hence, we propose that, according to the goal that they want to help their trainees to reach, they can design practice conditions encouraging one demand over the other. For example, constant practice appears to encourage learners to favor movement control over anticipation of future movements, it may be relevant for the speed climbers as they always perform on the same route, and they need to accurately use the holds to apply a maximum of force to gain speed. On the opposite, lead climbers may rather develop gaze behaviors facilitating adaptation to constraints by giving themselves more time to search for visual information to be able to perform adaptively on various novel routes. From this perspective, our results suggest that variable practice would be more suitable. Although not analyzed in the current thesis, the benefits of variable practice to performance on new routes may also reside in the development of effective visual exploration of the route during preview periods, particularly (i) to attune to affordances offered by the route and (ii) to reduce and guide exploratory activity during the climbs (Seifert et al., 2017).

The Manipulation of Interacting Constraints

In the **Chapter 5**, we designed a scanning procedure to evaluate the behavioral flexibility of the participants, that is their ability to demonstrate functional variability to adapt to different sets of constraints (Seifert, Komar, et al., 2016). The scanning procedure was designed by manipulating the route design and the instructions so that participants were confronted to a total of nine conditions. The interaction between these task constraints to create these nine conditions could be neutral (i.e., there were no instructions given), congruent (i.e., the instructions encourage to perform a hand coordination pattern that suit the route design) or incongruent (i.e., the instructions encourage to perform a hand coordination pattern that compete with the route design). The participants' climbing patterns clearly changed according to the instructions between congruent and incongruent route-instruction conditions. It appears that the instructions directed the participants' intentions during the climbs, which amplified and/or reduced behavioral information (Pol et al., 2020; Schöner et al., 1992). It also emphasizes that instructions act as constraints channeling the search for movement solutions (Newell & Ranganathan, 2010). Indeed, the given instructions encouraged the exploration of alternative movement solutions than those which were the most salient according to the route design, particularly in the incongruent conditions. Also, some participants were (mainly during the pre-test) performing the same hand coordination patterns on all the routes in the neutral conditions. In these cases, the instructions pushed them out of their comfort zone to explore other hand coordination patterns, which they appeared to be less familiar with. In the context of this scanning procedure, the instructions promoted an internal focus of attention as it invited participants to perform a particular movement form (in opposition to external focus of attention, where participant rather focus on the effect of their movements on the environment) (Peh, Chow, & Davids, 2011). However, it was not prescribed how and where to perform the demanded coordination pattern on the climbing routes, which provided some space for participants to explore how these coordination patterns could cooperate with the performance environment. Yet, we also observed that some participants did not change their behavior although instructions changed. This stresses that instructions need to be assimilated by performers to act as task constraints, otherwise they are only environmental information (provided via social systems) that performers can ignore if they consider that it does not suit their goal (Balagué, Pol, Torrents, Ric, & Hristovski, 2019). Thus, manipulating simultaneously multiple task constraints can foster performers' exploration of different movement solutions to achieve the task-goal. Yet the behaviors that emerge from the designed set of constraints remain dependent of the relationship between the performers and their environment.

Conclusion

In relation to its first objective, this thesis deepened the understanding of the change in exploratory activity that support skill learning and transfer in complex perceptual-motor tasks with respect to the Ecological Dynamics framework. More precisely, the findings supported that the dominant function of exploratory activity, reflected mainly by performers' gaze behaviors, switched from searching the environment for affordances to guiding movements with practice. The conditions of practice were shown to shape learners' exploratory activity in two opposite directions: over-specializing to movement control in the learning context or facilitating adaptations to new performance contexts. These entail that the examination of the effects of interventions on exploratory activity should be more central to understand perceptual-motor skill learning and transfer from an Ecological Dynamics perspective as exploratory activity is what maintains performers in contact with their environment.

The second objective was to investigate the effects of imposed and self-controlled variable practice conditions on behavior. Giving control to learners over the rate at which their learning condition changed appeared more respectful of their learning dynamics regarding their performance curves and change in behavioral flexibility. We suggest that this condition helps learners to more actively self-regulate their interaction with the practice environment in comparison to the learners in imposed learning conditions. However, the changes in gaze behaviors observed with practice also suggest that the self-controlled condition was less challenging than the imposed condition, as self-controlled conditions did not guide participants toward more proactive gaze behavior. These findings call for more research on the effects of self-controlled practice from an Ecological Dynamics perspective. The addition of a yoked group to control for the potential effects of the given autonomy on behaviors would be advised.

The data collections and treatments of the two experiments were challenging and time-consuming, notably to track each learner's performances and gaze behaviors over 13 sessions and to implement a self-controlled practice. However, these efforts offered some stimulating and sometimes surprising results that provided new avenues for future research about learning dynamics and exploratory activity in skill learning. The use of climbing tasks appears relevant to investigate exploratory activity in a performance context where performers are surrounded by affordances as it enables to examine a multi-articular movement task while maintaining control over experimental conditions. Indeed, indoor climbing enables to manipulate the properties of the environment with which participants interact. This facilitates the control over task parameters as illustrated by the reduction of the complexity of the environment between the two experiments presented in this thesis. Indeed, we chose to standardize the holds design to be able to focus on the chaining of climbing actions and to invite novice participants. Thus, although we lost some ecological validity, the task used in the second experiment is certainly more transversal to other sporting activity because of the problem of limbs coordination that it presented to performers.

A further perspective stemming from this thesis is to investigate the dynamics of exploratory activity and notably the gaze behaviors to apprehend how the visual control of actions evolves with practice in a complex multiarticular task. As shown by the exploratory analyses (**Appendix B**), we may expect that the functions of the gaze would change over different timescales and we may also expect the dynamics to be nonlinear but closely related to the participants' exploration/exploitation of different chain of limbs actions. This would complement previous research on the learning dynamics of coordination patterns (e.g., Chow et al., 2008; Komar et al., 2019; Nourrit et al., 2003).

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Appendices

Appendix A: Pictures of the Experimental Settings

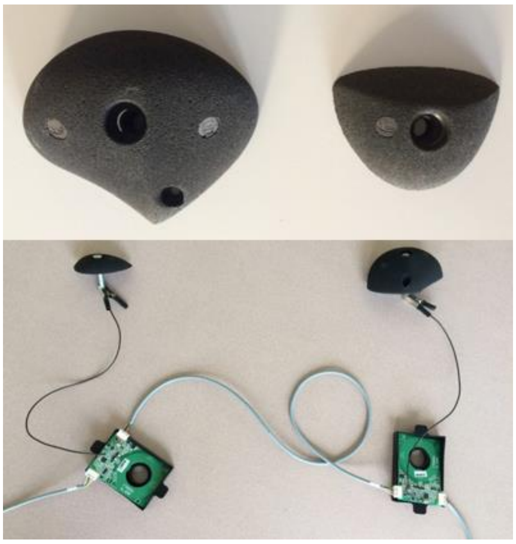

Figure 36. The instrumented holds and the Luxov® Touch system.

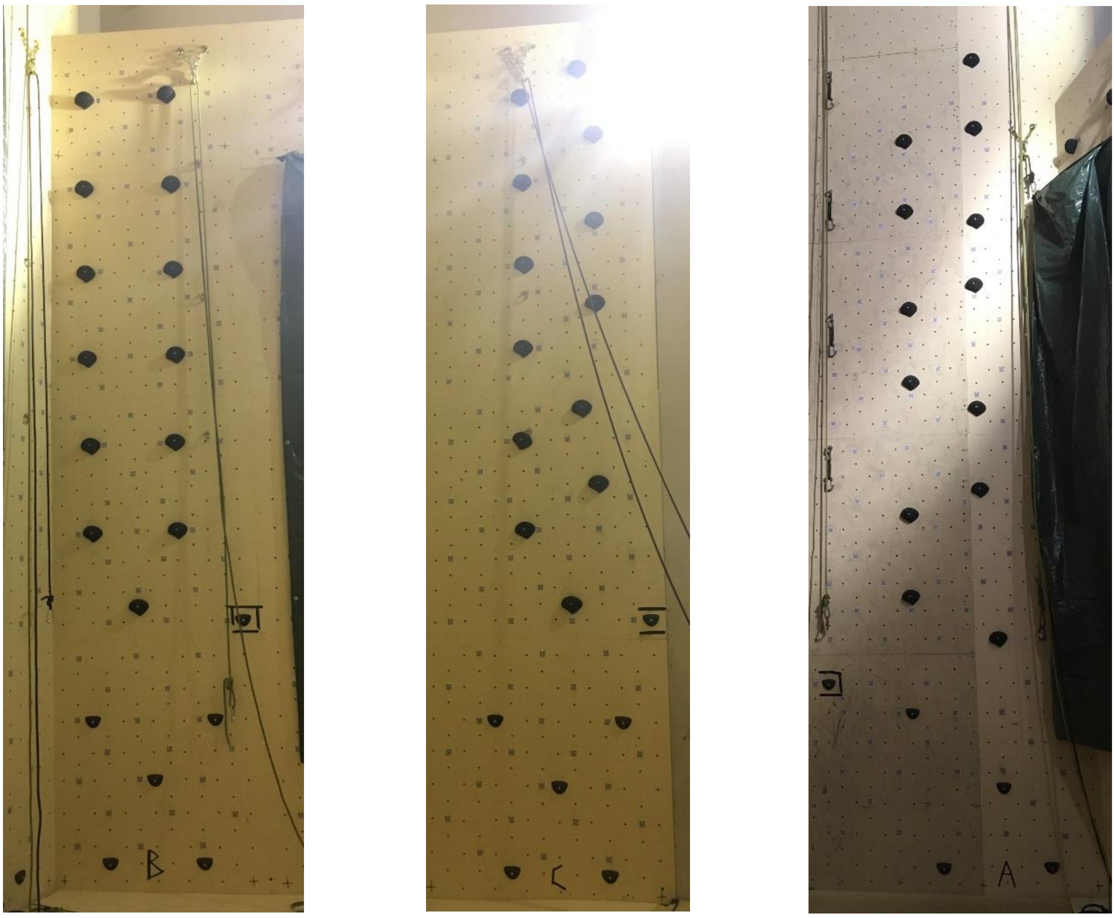

Figure 37. Routes designed for the test sessions.
The neutral, alternation and repetition route, respectively.

Figure 38. Training and transfer route

Figure 39. Variant routes 1 to 6.

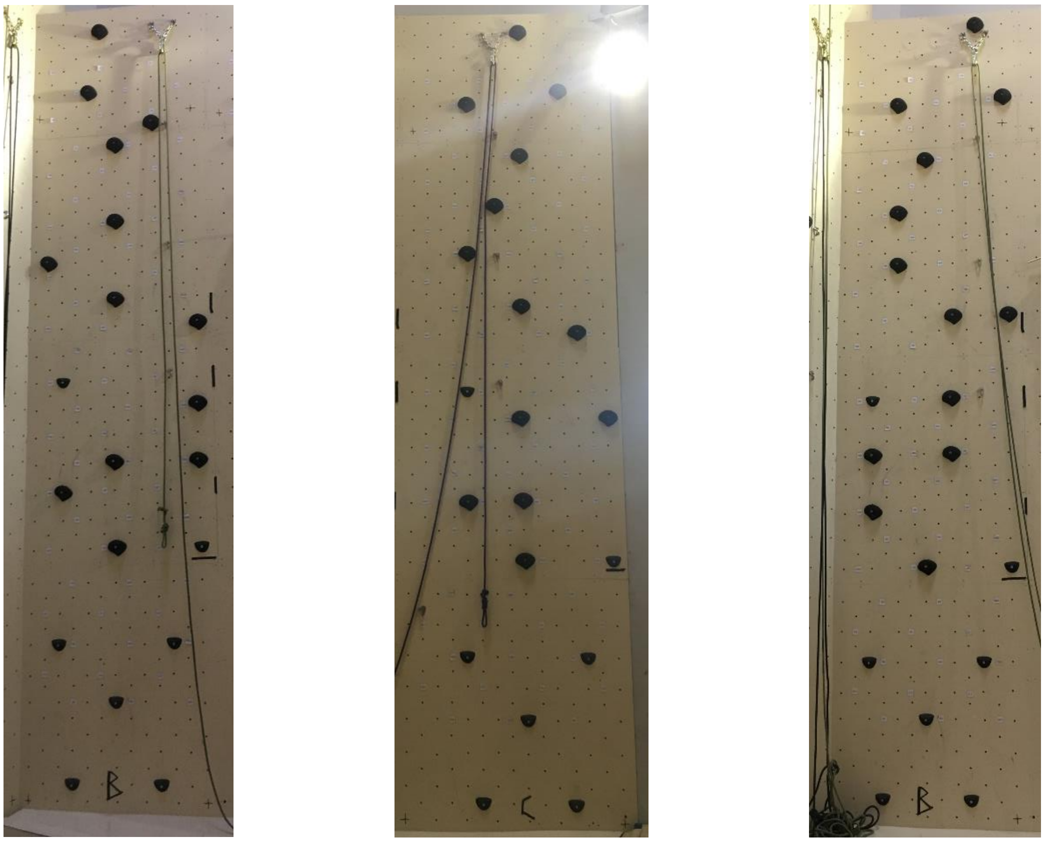

Figure 40. Variant routes 7, 8 and 9.

Appendix B: Exploratory Analyses of the Change in Gaze Behaviors with Practice

The aim of this exploratory study is to investigate the effect of a constant learning protocol on the performance and the gaze behaviors of learners in a climbing task. The designed climbing task aimed at focusing on the ability of participants in finding an optimal chain of climbing movements that would limit the displacements of their center of mass and the stops during the climbs, which we refer to as gaining in fluency. As the climbers always practiced on the same climbing route, we expect that they will improve their fluency and that it will be accompany by a less complex gaze path. As the participants always practice on the same route, we may expect a decrease in the proactive function of the gaze as the online control of hand movements may be favored to gain in accuracy in the climbing movements and to keep improving the climbing fluency.

Method

Participants

We only considered the six participants who finished the constant practice protocol for this study.

Procedure and Data Collection

The method is the same as in the Chapter 7. The difference being that we used the data from the six trials on the training route in the first and last session of the constant practice conditions.

Statistical Analyses

Two factors repeated measures ANOVA (RM-ANOVA) were performed on the geometric index of entropy and the conditional visual entropy. The within participants factors were Trials (6) and Sessions (2).

The mixed-effects model (LMM) analyses were performed on the gaze dependent variables (onset, offset time, and duration of gaze visit before contact) with Handholds (AOI label) and Participants as random effects and Trials (6), and Sessions (2) and their interaction as fixed effects. Statistical Analysis

All the statistical analyses were performed in R (R Core Team, 2019).

Linear mixed-effects model analyses (LMM) were performed on the gaze dependent variables (onset, offset time, and duration of gaze visit before contact) with AOI (handhold label) and Participants as random effects and different fixed effects according to the study (Baayen, Davidson, & Bates, 2008; Magezi, 2015). The random effects structure in all LMM initially included a participant and handhold adjustments of the intercept (i.e., two random intercepts) and an adjustment of the factor Session by-participant and by-handhold (i.e., two random slopes), this structure was simplified only if the mixed-effects linear model could not converge (Barr, Levy, Scheepers, & Tily, 2013). We chose this solution (i) to avoid averaging the values over the 11 handholds on each trial and comparing "means of means" and (ii) because this method is more flexible to deal with missing data. A loglikelihood ratio test (reported as LLR χ^2 (DF)) was performed to compare the models fitted with and without each of the fixed effects with the anova() function. The models were fitted with the lme4 package (Bates, Mächler, Bolker, & Walker, 2015). The fixed and random effects are calculated with a standard maximum likelihood criterion for the models used for the comparisons, whereas the estimates (β) of the effects and their standard error (*SE*) in the final model are calculated with restricted maximum likelihood criteria (Luke, 2017; Magezi, 2015).

Results

Geometric Index of Entropy.

The dynamics of the participants' climbing fluency are displayed on the **Figure 41**. The RM-ANOVA performed on the spatial fluency indicator showed a large Session effect [$F(1,5) = 50.204$, $p < .001$, $\eta_G^2 = .766$] but no Trials [$F(5,25) = 1.274$, $p = .306$, $\eta_G^2 = .031$] or Trial x Session effects [$F(2.29,11.47) = 0.981$, $p = .415$, $\eta_G^2 = .022$, Mauchly test was significant $p = .022$ so the Greenhouse-Geisser correction was applied with $\varepsilon = .459$]. Thus, the climbing fluency of the participants improved with less complex hip trajectories in session 10 ($M = 0.509$, $SD = 0.111$) comparing to the session 1 ($M = 1.18$, $SD = 0.247$, $p < .001$). The results did not show any trend during the sessions.

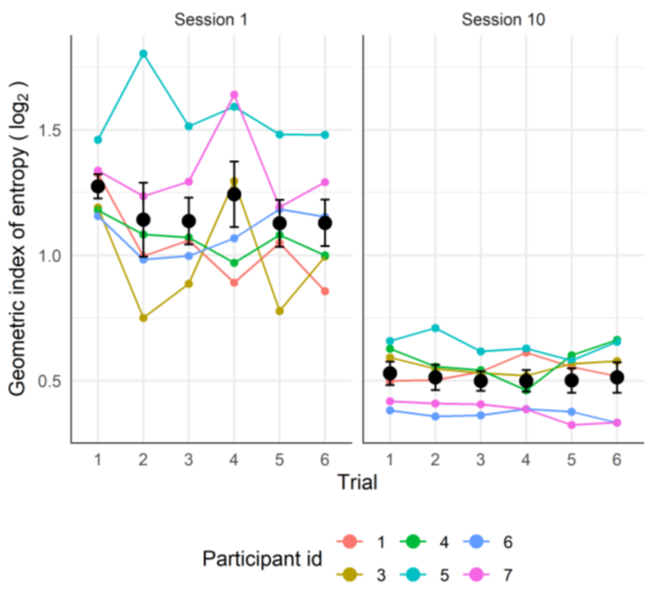

Figure 41. Dynamics of the climbing fluency.
The black point represents the trial mean and the error bars its standard error. The colored/greys points and lines represent each participant's dynamics.

Complexity of the Gaze Path

Regarding the measures of the complexity of the gaze path, we performed the RM-ANOVA although the data on the session 10 were not normally distributed according to the Shapiro-Wilk test. When looking more closely to the data on the session 10, it appears that the value of 12 gaze visits and an entropy of 0 value are frequent (n = 23 and n = 22 respectively). This means that participants looked at the 12 handholds in the order of appearance in the climbing route, thus reaching the 0 in visual entropy.

Number of Gaze Visits

The RM-ANOVA applied to the number of gaze visits showed a large effect of the factor Sessions [$F(1,5) = 42.678$, $p = .001$, $\eta_G^2 = .715$], a medium effect of the factor Trials [$F(5,25) = 6.179$, $p < .001$, $\eta_G^2 = .218$] and a medium effect of the interaction between the factors Session and Trial [$F(5,25) = 5.547$, $p = .001$, $\eta_G^2 = .197$]. These results showed that the participants decreased the number of gaze visits during their ascents between session 1 (M = 20.31, SD = 4.43) and session 10 (M = 12.22, SD = 0.898), and they also decreased this number within the first session between the three first trials and the three last trials (M = -4.06, SD = 3.42) whereas it was stable during the session 10 (M = 0.22, SD = 1.26) (**Figure 42A**).

Visual Entropy

Similarly, the RM-ANOVA applied to the visual entropy scores showed a large effect of the factor Session [$F(1,5) = 34.401$, $p < .002$, $\eta_G^2 = .684$], a medium effect of the factor Trial [$F(5,25) = 4.524$, $p = .004$, $\eta_G^2 = .154$] and a medium effect of the interaction between the two factors [$F(5,25) = 5.555$, $p = .001$, $\eta_G^2 = .162$]. These results showed that the complexity of the participants' gaze path decreased between the session 1 ($M = 0.393$, $SD = 0.205$) and the session 10 ($M = 0.027$, $SD = 0.038$), and it also decreased within the first session between the three first trials and the three last trials ($M = -0.175$, $SD = 0.131$) whereas it was stable during the session 10 ($M = 0.0041$, $SD = 0.047$) (**Figure 42B**).

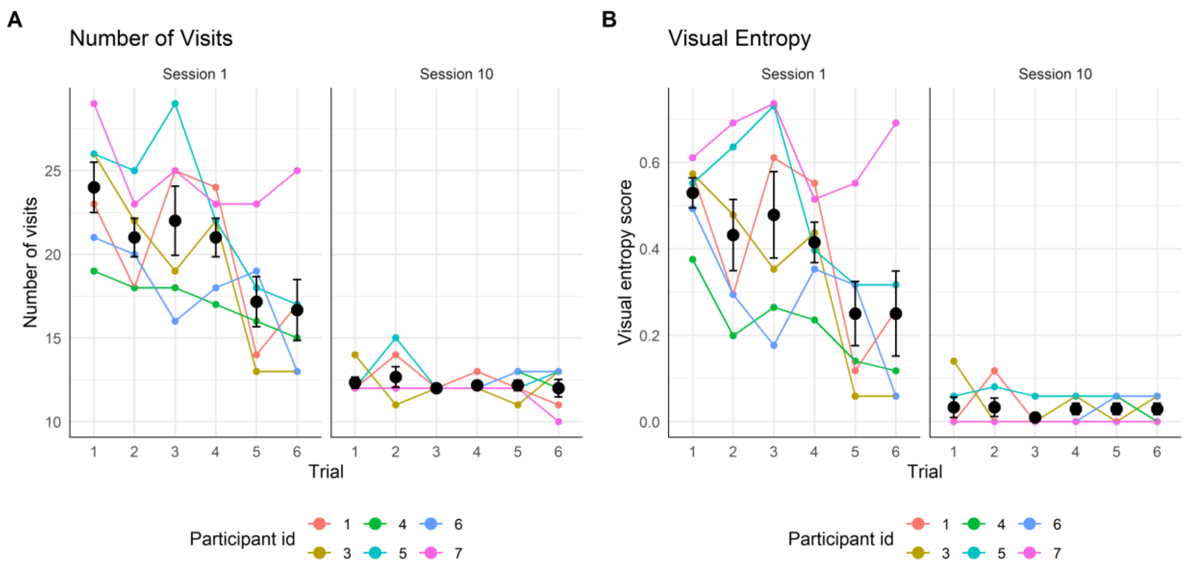

Figure 42. Dynamics of the gaze path complexity measures.
Panel A shows the number of gaze visits and Panel B the visual entropy scores. The black points represent the trials mean and the error bars their standard error. The colored/greys points and lines represent each participant's dynamics.

Characteristics of the last Gaze Visit

Gaze Onset

The LMM revealed that time of the gaze visit onset was also affected by the effect of the variable Session [$\beta = 166.970$, $SE = 41.022$, LLR χ^2 (1) = 15.236, $p < .001$] but not by the effect of the variable Trial [$\beta = 0.313$, $SE = 6.051$, LLR χ^2 (1) = 0.570, $p = .450$] nor the interaction between Session and Trial [$\beta = 5.433$, $SE = 8.300$, LLR χ^2 (1) = 0.460, $p = .498$]. Thus, the gaze visit started earlier in the session 1 ($M = -597$ms, $SD = 226$ms) than in the session 10 ($M = -413$ms, $SD = 161$ms) (**Figure 43A**).

Gaze Offset

Regarding the time of the gaze offset, the random effects structure was simplified and included a participant and handhold adjustments of the intercept and a by-participant adjustment of the main factor Session. The LMM revealed that the time of the gaze visit offset was affected by the effect of the variable Session [β = 72.915, *SE* = 27.051, LLR χ^2 (1) = 7.310, *p* = .007] but not by the effect of the variable Trial [β = 0.608, SE = 3.532, LLR χ^2 (1) = 0.042, *p* = .838] nor the interaction between Session and Trial [β = -0.2122, *SE* = 4.947, LLR χ^2 (1) = 0.002, *p* = .966]. These results showed that during the session, the time of the gaze offset did not change significantly but it occurred later after practice (session 1: *M* = -33ms, *SE* = 137; Session 10: *M* = 41ms, *SD* = 117ms) (**Figure 43B**).

Gaze Duration

The random effects structure of the LMM was simplified for the duration of the gaze visit. It included a participant and handhold adjustments of the intercept and a by-participant adjustment of the main factor Session. The fit of the linear mixed-effect models was improved by the fixed effect Session [β = -84.645, *SE* = 44.712, LLR χ^2 (1) = 6.952, *p* = .008] but not by the effect Trial [β = -1.881, *SE* = 6.753, LLR χ^2 (1) = 0.929, *p* = .335] nor the interaction between Session and Trial [β = -4.865, *SE* = 9.281, LLR χ^2 (1) = 0.275, *p* = .600]. Thus, the duration of the last gaze visit decreased between the session 1 (*M* = 556ms, *SD* = 248ms) and the session 10 (*M* = 460ms, *SD* = 196ms) (**Figure 43C**).

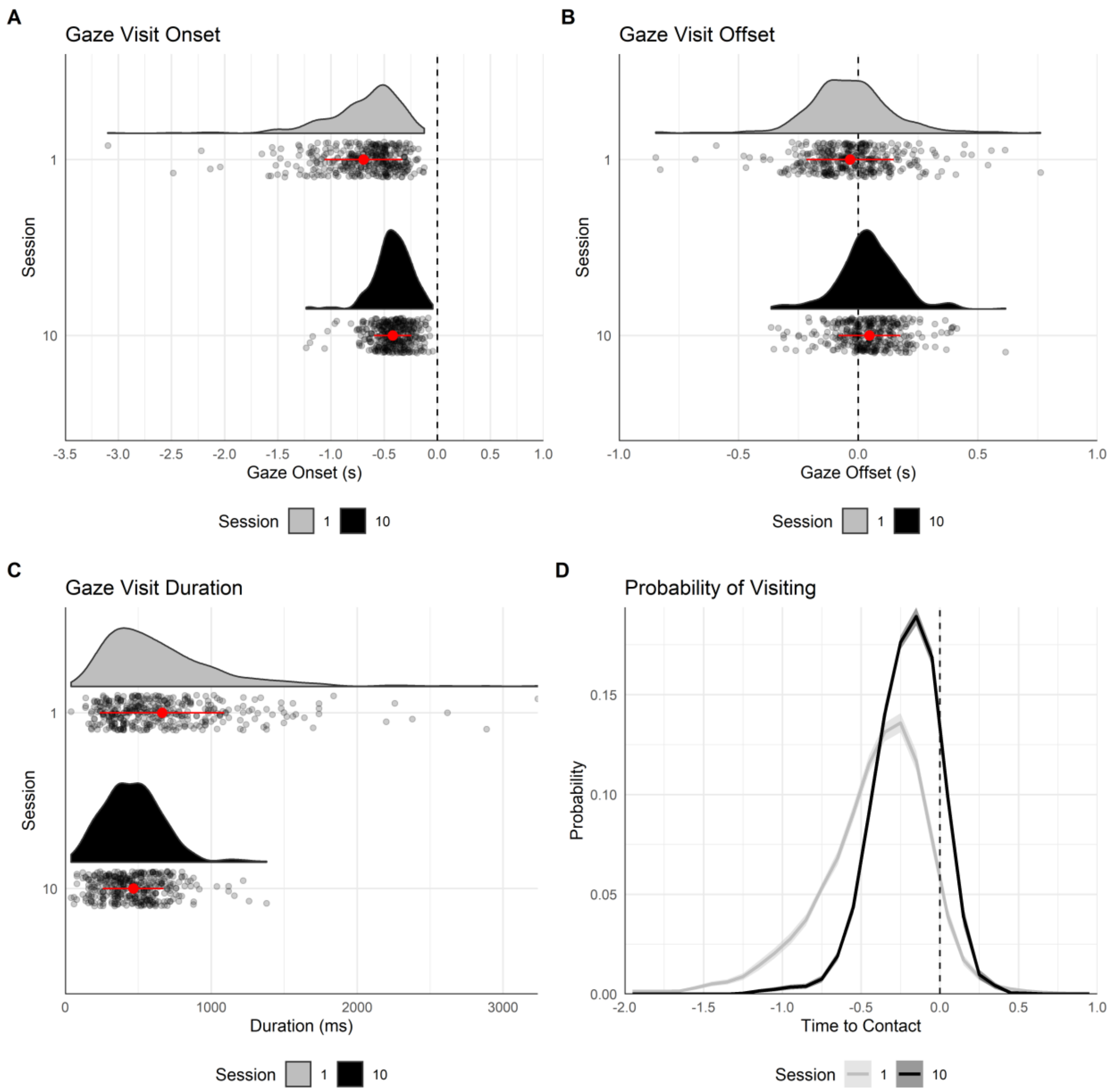

Figure 43. Characteristics of the last gaze visit before the hand contact the handhold.
In panels A, B and C, each point represents one gaze visit before a contact with a handhold, the halves violin shows the density of points, the red/grey point with the error bar refers to the mean of all the gaze visits and the standard deviation around the mean. The color of the half violin refers to the learning session: in grey, session 1 and in black, session 10. Panel A shows the starting time of the gaze visit, with 0 and the vertical dashed line representing the time of the hand contact with the handhold. Panel B shows the ending time of the gaze visit, with 0 and the vertical dashed line representing the time of the hand contact with the handhold. Panel D shows the duration of the gaze visit. Panel D shows the probability that the gaze visits the AOI. Lines refer to the mean probability across participants and the shade round the line represent the standard error of the mean. Mean and standard error were calculated for each frame of 100-ms.

Discussion

This exploratory study aimed at investigating the adaptations of the climbing fluency and the gaze behaviors at two timescales: within a session and between the first and last session of a constant training protocol. More precisely, it appears that participants gaze path became more organized within the first session and became even more organized between session 1 and 10. On the session 10, the gaze path appeared to be quite consistent throughout the trials, with the number of visits being maintained around 12 and the visual entropy around 0, meaning that the gaze went from handhold to handhold without “search” during the climbs. The characteristics of the last gaze visit did not change within the sessions. The adaptations in onset time, offset time and duration only appear between early and late practice. More precisely, the duration of the gaze visit became shorter, and the gaze visit started and finished latter on the session 10 compared to session 1, thus, the distribution of the probability of gaze visit narrowed and the peak drifted closer to the time of contact (**Figure 43D**). Therefore, the results suggest that learners first rapidly decrease their search of their environment and then adapt at a longer timescale their visual control of hand actions.

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Apprentissage et Transfert Perceptivo-moteur :
Effets des Conditions de Pratique sur l'Activité Exploratoire dans une Tâche d'Escalade

Résumé : L'objectif principal de cette thèse est d'examiner les effets de différentes conditions de pratique sur l'activité exploratoire qui accompagnent l'apprentissage perceptivo-moteur et facilitent le transfert d'habiletés en utilisant des tâches d'escalade. Pour cela, cette thèse s'est d'abord intéressée à étudier l'effet de l'ajout de variabilité dans la pratique au cours de l'apprentissage. Cette variabilité de pratique a été induite par des variations d'environnement d'apprentissage. Cette variabilité induite est censée favoriser le transfert d'habiletés en guidant l'activité exploratoire des apprenants et en développant la flexibilité du répertoire comportemental. Bien qu'il soit connu que les dynamiques d'apprentissages sont différentes d'un individu à l'autre, les conditions de pratique sont généralement aménagées indépendamment des apprenants. Ainsi, un second objectif était d'examiner chez les apprenants l'effet d'avoir la possibilité d'auto-contrôler les conditions de pratique (i.e. le degré de variabilité) sur les dynamiques individuelles.

Les résultats suggèrent que la fonction dominante de l'activité exploratoire des apprenants change avec l'apprentissage, passant de l'exploration d'affordances au contrôle des mouvements. Les comportements visuels que les apprenants utilisaient pour guider les mouvements de leurs mains étaient sensibles aux conditions de pratique, de sorte que la pratique constante favorisait un contrôle visuel direct des mouvements tandis que les conditions de pratique variables développaient un comportement visuel proactif qui pouvait être utilisé dans un nouveau contexte de performance. Cependant, la plus grande variabilité comportementale observée dans les conditions de pratique variable n'a augmenté ni la quantité d'apprentissage des participants, ni leur flexibilité comportementale. Ces résultats plaident à définir l'apprentissage d'habiletés comme hautement spécifique à l'environnement et mettent en avant le fait que les tâches perceptivo-motrices complexes offrent une importante richesse de possibilités de mouvement, y compris dans une condition de pratique constante. La condition de variabilité autocontrôlée semble faciliter le développement de la flexibilité comportementale des participants leur permettant d'exploiter la pratique variable de façon individualisée et donc plus efficacement. Ceci indique que cette condition peut encourager les participants à autoréguler leurs performances plus activement afin de respecter au mieux leur propre dynamique d'apprentissage.
Mots-clés : Perception-Action, Dynamique Ecologique, Comportement visuel, Affordances, Acquisition d'habiletés.

Perceptual-motor Learning and Transfer:
Effects of the Conditions of Practice on the Exploratory Activity in a Climbing Task

Abstract: The main objective of this work was to examine the changes in performers' exploratory activity that accompany skill learning and support skill transfer using climbing tasks. Moreover, this thesis investigated whether infusing variability in practice with task variations designed by manipulation of the learning environment foster skill transfer by developing learners' behavioral repertoire and guiding learners' exploratory activity. Although learning dynamics are known to be different between individuals, variable practice conditions are usually scheduled regardless the learners' dynamics. Thus, a final aim of this work was to examine whether giving learners the opportunity to self-control their practice schedule offered learning conditions more respectful of the individual dynamics.

The results suggested that the dominant function of the learners' exploratory activity changed with learning, from exploring for climbing affordances to guiding the climbing movements. The gaze patterns that learners used to visually guide their hand movements were sensitive to the practice conditions, so that constant practice promoted online gaze control whereas the variable practice conditions developed a proactive gaze pattern which appeared to transfer to new performance context. However, the highest behavioral variability observed during variable practice conditions, did not enhance the participants' learning rate nor their behavioral flexibility, supporting that skill learning was specific to the performance context and that complex perceptual-motor tasks offers a rich landscape of movement possibilities, even in a constant practice condition. The self-controlled variability condition appeared to have facilitated the participants' development of their behavioral flexibility and to have helped them to individualize the exploitation of the variable practice condition (i.e. in more effective way), which suggests that this condition supported participants to more actively self-regulate their performance dynamics.
Keywords: Perception-Action, Ecological Dynamics, Gaze behavior, Affordance, Skill acquisition.